APPENDIX A
STS RENDEZVOUS/PROX OPS EXPERIENCE

Over the course of several years a wide variety of RNDZ and PROX OPS experience has been accumulated. General material has already been incorporated into the body of this handbook, but a mission-specific enumeration of "lessons learned" is presented in this appendix.

RNDZ/PROX OPS missions to date are summarized in table A-I. These include missions for which planning was done, but which were cancelled.

The material in this section has been extracted from flight crew reports, from technical reports, from FDF Rendezvous and Prox Ops books, and from DM43 archives.

TABLE A-1.- STS RENDEZVOUS/PROX OPS MISSIONS

Mission	Launch date	Activities
STS-7	1983 June 18	SPAS-01 PROX OPS
STS-10	1983 Nov.	IRT - mission cancelled
STS 41-B	1984 Feb. 03	IRT practice TRK
STS 41-C	1984 Apr. 06	LDEF deploy; SMM RNDZ (twice)
STS 41-F	1984 Aug.	Spartan - mission cancelled
STS 51-A	1984 Nov. 08	Palapa/Westar RNDZ /recovery
STS 51-D	1985 Apr.	LDEF retrieve - cancelled
STS 51-DR	1985 Apr. 12	Syncom contingency RNDZ
STS 51-G	1985 June 17	Spartan-1 deploy/retrieve
STS 51-F	1985 July 29	PDP PROX OPS
STS 51-I	1985 Aug. 27	Syncom RNDZ/repair
STS 61-B	1985 Nov. 27	OEX DAP test
STS 51-L	1986 Jan. 28	Spartan Halley (Challenger accident)
STS 61-J	1986	HST rendezvous: cancelled
STS 61-I	1986 Sep	LDEF retrieve: cancelled

A. STS-7 (STS 31-C) was launched June 18, 1983/1133 GMT, with a crew of Crippen (CDR), Hauck (PLT), Fabian (MS1), Ride (MS2), and Thagard (MS3). STS-7 performed two sessions of PROX OPS with the Shuttle Pallet Satellite (SPAS) to prove out sensors, flight procedures, and plume impingement effects.

The "lessons learned" summary from DA8 relates that

- Radar performance was good (angle rate data noisy).
- RMS operations worked well, variable RMS tip-off rates at release.
- Verified propellant costs for V-BAR and inertial flyaround.
- Plume susceptibility outside quiet zone is dramatic (not LOW Z).

* * * *

The STS-7 experience was summarized by Crippen and Hauck in their conference paper, Orbiter Operations in Close Proximity to Free-Flying Satellites, or Formation Flying in Space. The following excerpts concern procedures:

During PROX OPS, one pilot was actively controlling the Orbiter from the aft station, while the other pilot was seated in the starboard pilot's seat, monitoring Orbiter systems, making any necessary inputs through the computers to the automatic flight control system, and acting as the prompter for the timeline. One of the MS's was at the port aft station to either control the robot arm during payload release and grapple operations, or to control the TV cameras for documentation or ranging (triangulation) purposes. A second MS was seated in the commander's (port) seat, monitoring, via telemetry, the health and commanding changes of the satellite, and of the attitude of the satellite. The third MS floated somewhere in the middle of the other four, taking both motion and still pictures of the operation.

As in any type of flight operation, fuel conservation is critical. A variety of fuel-saving techniques was evaluated during preparations for STS-7. Several are obvious - a few others are not. Since the SPAS satellite was released nonpropulsively from the Orbiter, they were both initially in the same orbit. Energy added to or subtracted from the Orbiter during back-away had to be compensated for later, after the desired stationkeeping position was established, to return the Orbiter to a stable orbit relative to the SPAS. A subsequent rejoin similarly required the expenditure of fuel to initiate the desired motion and a later fuel usage to null that motion when the regrapple position was attained. The lessons are obvious and are direct corollaries of how we manage fuel with aerodynamic machines: Do not use afterburner if military thrust will do. Do not use military if idle will do, and in the no-drag environment on orbit we have the advantage of being able to adhere to the maxim: shut down the engines if you are not using them to move the vehicle.

On STS-7 the orbital altitude of the Shuttle was approximately 160 n. mi. with a resultant 90-minute orbital period. Thus, every hour and a half Challenger passed through a full day/night cycle, with 55 minutes of daylight and 35 minutes of night. MNVR's in close proximity to the SPAS were designed to be accomplished during daylight, constrained such that closure rates were phased and of sufficient magnitude to complete regrapple in daylight. Obviously, to conserve RCS propellant, it was desirable to make the smallest Orbiter velocity changes possible, compatible with lighting constraints and other test objectives.

In addition to this "slow is good" rule, there is another, which is not quite so obvious: Do not put energy into out-of-plane MNVR's. As stated earlier, since SPAS was released from the Orbiter nonpropulsively, in an ideal environment with no other perturbations, their orbit planes should have remained coincident. Any (small amount of) energy added to either spacecraft perpendicular to the orbit plane resulted in a very small tilting of the affected orbit plane, but the resulting relative motion was periodic. Thus, as long as the out-of-plane motion or misalignment did not overly complicate the formation flying problem, no propellant was used to null it. In general, 10° of azimuth sighting deviation (with the COAS) was used as the boundary for making out-of-plane corrections.

Finally, a few words on the use of automatic versus manual control modes are in order. As was mentioned previously, there are several AUTO Orbiter rotation modes which are available. Early in flight-techniques development it was determined that whenever both translational and rotational MNVR's were required simultaneously, it was much easier (and more efficient) to let the AUTO mode perform the ROT while the translation was done manually. Thus, attitude MNVR's were designed to take advantage of the AUTO rotational capability inherent in the DAP.

PROXIMITY OPERATIONS

Phase One

The initial portion of the PROX OPS involved the following: releasing the SPAS above the Orbiter in an Earth-oriented sense. A translation of the Orbiter was then initiated away from the SPAS along the Earth R-BAR. At 200 feet below the SPAS, the orbital mechanics effects were allowed to let the Orbiter proceed in front of the SPAS while the pilot manually rotated the Orbiter about its Y axis to maintain the SPAS in the COAS (fig. A-1). At a range of 1000 feet, the opening rate was nulled, the Orbiter placed in inertial attitude hold, and a +X translation was initiated to move the Orbiter upward toward the SPAS V-BAR. Upon arrival at the V-BAR, the Orbiter was placed in a tail-down, local-vertical flying mode and all relative rates were nulled. Stationkeeping at the 1000-foot point on the V-BAR was maintained a little over 2 hours. A 1-foot-per-second translation was then initiated toward the SPAS. Appropriate braking gates were used on the approach.

Relative rates were nulled with the SPAS in the field of view of the robot arm RMS wrist camera. The SPAS was then successfully grappled with the RMS.

The initial release on the R-BAR by the RMS was very stable, as were all releases. At the time of the release, the Orbiter was in a free-attitude control mode (MAN PULSE) and the SPAS was over the payload bay. Visibility at this point was excellent. After the stability of the SPAS was noted, VERN attitude control in a bottom-down, nose-forward, local-vertical mode was selected for the Orbiter. Rotation of the SPAS about each of its axes was commanded and checked. During this check, a very slight opening rate on the SPAS was noted.

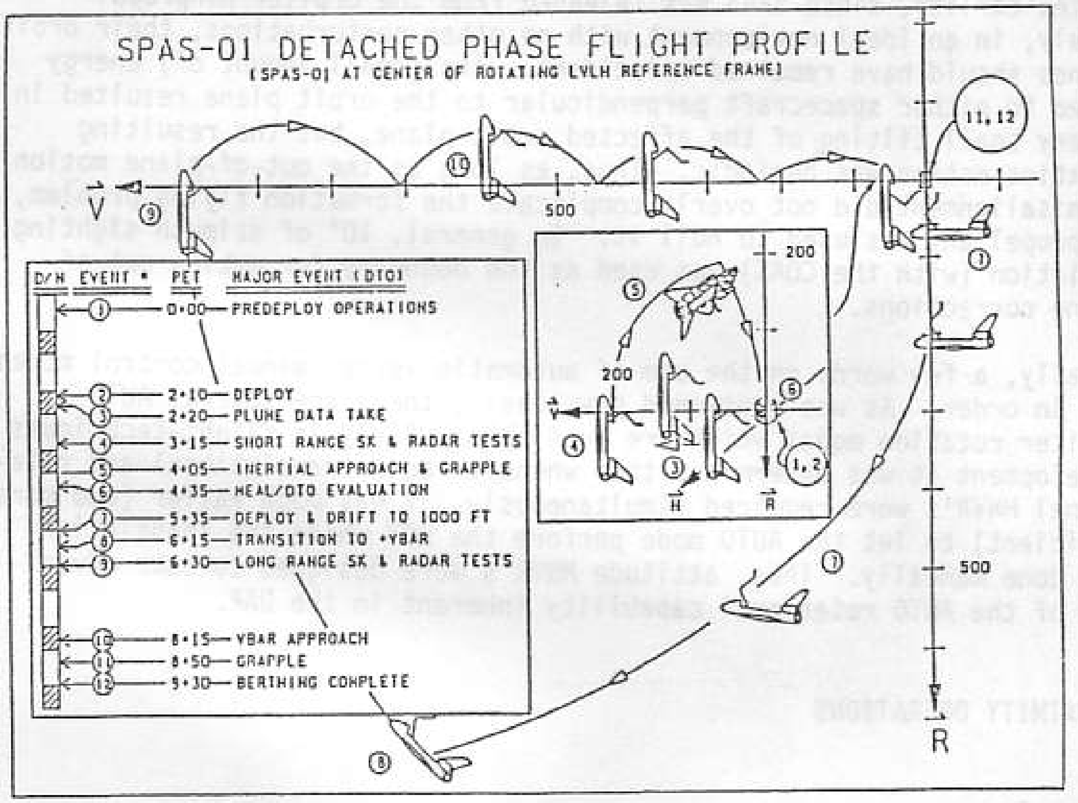

Figure. A-1.- SPAS profile-1.

After the check was complete, NORM jets in the low Z mode were used to initiate an opening rate of approximately 0.25 ft/s. As was previously stated, the low Z mode fires + and - X thrusters for +Z translation to minimize plume impingement on the free-flying satellite. Pulse size for the initial translation was 0.05 ft/s. Then a pulse size of 0.01 ft/s was selected for fine control. This was accomplished by switching between DAP's A and B. Thereafter, control was manually switched back and forth between these two pulse sizes as the control task demanded. Control inputs were also initiated to move the Orbiter aft, such that SPAS moved forward toward the COAS.

At approximately 70 feet, search was initiated on the radar and it locked on shortly thereafter. Both range and range rate were very stable and remained that way. The line-of-sight rates were observed to be intermittently stable and oscillatory with an occasional OFF flag. At an indicated range of 200 feet, ROT about the Orbiter X and Z axes were placed in inertial attitude hold and the Y axis in a free mode. Vernier jets were also selected.

The 200-foot point was reached at approximately the same time the SPAS had reached the field of view of the COAS. At this point the RHC was used in a PULSE mode (pulse size 0.01 deg/s) to maintain SPAS in the COAS in the pitch axis only. Roll and yaw were placed in inertial altitude hold (MAN DISC RATE). Translational inputs were terminated, and the orbital effect of being in a lower orbit was allowed to cause the Orbiter to accelerate ahead of the SPAS. No attempt to correct out-of-plane motion was made throughout phase one until the final approach. The SPAS was placed in inertial at this point with minor attitude corrections to optimize pointing for photography and television.

At a range of 1000 feet, the Orbiter was placed in inertial attitude hold and the opening rate, which was approximately 1.3 ft/s as indicated by the radar, was nulled. Since these firings were primarily retrograde, they would tend to make the Orbiter fall to an even lower altitude. However, motion of the SPAS in the COAS was used as the cue for initiating the +X translations necessary to maintain the SPAS in the center of the COAS. This initiated the transition toward the V-BAR. During this transition, the radar range rate readout was used to null opening and closing rates. Upon reaching the V-BAR as indicated by the ADI and UNIV PTG display, the Orbiter was placed in a tail-down, bottom-forward, local-vertical flying mode. Again, using the motion of the SPAS in the COAS, the upward motion of the Orbiter, with respect to the SPAS, was nulled with -X translational inputs. The SPAS was placed approximately 2.5° low in the COAS to account for placing the Orbiter center of gravity on the velocity vector of the SPAS. Radar range rate was again nulled.

Long-range stationkeeping was initiated by opening up the normal jet ATT DB from 2° to 5°. This was to minimize the possibility of attitude control NORM jet firings when a translational input was made. Vernier jets with a 0.5° DB was the mode normally selected while stationkeeping. Momentary selection of normal jets was made when a translational input was required. With the availability of radar range and range rate, this was a very easy task. There were periods of up to half an hour without the requirement for crew inputs.

Two radar tests were performed at the 1000-foot point. Each involved maneuvering the Orbiter 20° out of attitude--one was a -Y (yaw) rotation and the other a +X (roll) rotation. Twenty degrees is on the edge of the radar search envelope. The radar lock was broken once the Orbiter was in attitude and the radar antenna was manually driven to zero in elevation and azimuth. Search was initiated while holding the offset attitude for the -Y rotation and after initiating the maneuver back to normal local vertical for the -X case. In both cases the radar achieved a lock-on in short order.

Night viewing was also evaluated at the 1000-foot point. Having the SPAS running lights on was the only satisfactory lighting configuration. The PLB bay lights had no effect on SPAS visibility. This was also true of the RMS end-effector light. A color television camera proved to be useless with the SPAS running lights turned off. The black and white camera was not evaluated because a cable-wrap problem prevented it from being properly positioned. While the SPAS was visible in the improved crew optical sight (ICOS) with the running lights on, the SPAS was barely discernible when they were turned off. ICOS night-SPAS visibility without running lights was so poor it would not have been detectable without prior knowledge of its position. The ICOS was not a satisfactory stand-alone night viewing aid. It should also be noted that this evaluation was made with a full moon, and that the first point that the SPAS was visible without running lights was approximately 300 feet. Also, it is important to note that stationkeeping at 1000 feet would not have been possible at night without the visibility provided by the running lights. Some means of illuminating satellites is mandatory when stationkeeping or making final approaches at night.

The final approach was initiated at night at a time designed to reach 200 feet at sunrise. This timing worked out very well. The normal jet DB was shrunk from 5° to 2°. A closing rate of 1 ft/s was initiated using the radar range rate. Orbital mechanics then dictates periodic up (+X) firings to keep the Orbiter on the V-BAR. Again, vernier jets were used except when a translational command was required. The braking technique used was at 500 feet to slow to 0.5 ft/s, at 400 feet to 0.4 ft/s, at 300 feet to 0.3 ft/s, and at 200 feet to 0.2 ft/s. From 200 feet until final stop, less than 0.2 ft/s closure rate was maintained. After slowing to 0.2 ft/s at 200 feet, low Z was selected for the remainder of the approach. Plus X translational inputs were made to move the SPAS aft where the RMS was positioned over the PLB. This position was the same as used for the release. Radar lock was lost at approximately 70 feet. The B television camera view showing both the RMS and SPAS was used to judge closure rate. The RMS and effector camera, which was pointing parallel to the Orbiter +Y axis, was used to null rates before turning the task over to the RMS operator. The Orbiter and the SPAS were placed in free drift prior to RMS grapple.

Phase Two

The afternoon (phase two) PROX OPS had two main objectives. First, to define the pressure field of a single (RCS) jet plume (fig. A-2). Second, to demonstrate the capability to MNVR the Orbiter to an inertial position out of the orbital plane of the satellite, and close to capture range from that position.

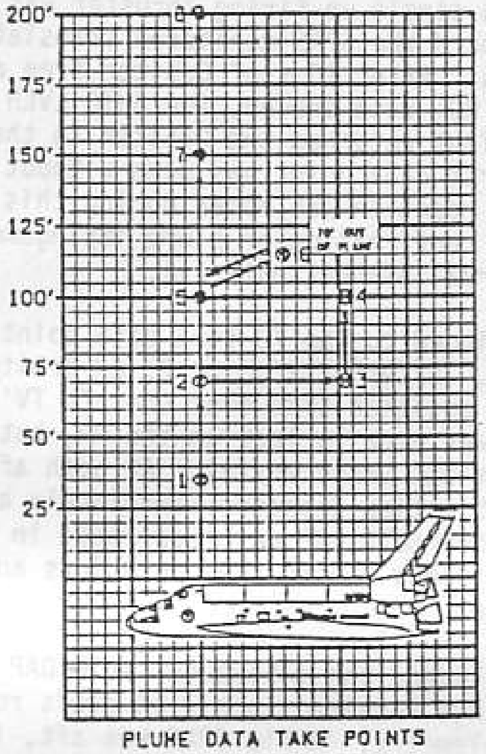

Figure A-2.- Plume data take points.

Satisfaction of both of these objectives was key to RNDZ with a crippled satellite (Solar Maximum) on Mission 13 with the intent of repairing it on orbit.

Due to a thermal problem with the SPAS avionics, the initiation of phase two was delayed for one orbit, permitting cooling of the avionics while the SPAS was parked on the end of the RMS in a benign attitude. To broaden the experience and evaluation base of PROX OPS, the two pilots swapped positions, as did two MS's.

To review, the Orbiter was now in the tail-to-Earth (-XLV) attitude with the belly in the direction of the velocity vector. The MS, using the arm, positioned the SPAS over, and 35 feet from, the overhead windows and then released it. The SPAS position was stable and the pilot used the THC to back away very slowly (0.2 ft/s) from the SPAS. The Orbiter ROT DAP was in the Earth pointing (LVLH) mode, which automatically kept the proper Orbiter orientation within the selected DB's. The DAP's were configured to provide .03 ft/s translation pulses when maneuvering between data points (DAP A), and to provide various pulse sizes (0.065 to 1 s pulse duration) when firing the forward up-firing thruster at SPAS during the data takes (DAP B). The pilot made small translational corrections to maintain the SPAS centered in the optical sight.

When Orbiter-to-SPAS separation had increased to 50 feet, as determined by using TV tilt angles for triangulation, the Orbiter attitude hold mode was inhibited and a single up-firing thruster was fired for 0.065 s. Recorders onboard the SPAS monitored translational accelerations and rotation rates. After 10 s of Orbiter free drift, during which a mild, nose-down ROT rate ensued, the AUTO LVLH DAP mode was reengaged and the autopilot returned the Orbiter to the specified tail-down attitude. This first data point was done without nulling opening rate. No SPAS attitude reaction was noted during this data take or any other. The only visual confirmation of plume impingement was a ruffling of some of the SPAS thermal blanket material.

The separation was continued to the 70-foot data point (number 2) where opening rate was nulled. After data point 2, an Orbiter forward translation was initiated to position SPAS over the aft TV's. During this translation an attempt was made to lock on the RR, but the initial attempt at about 80 feet was unsuccessful. At both aft data points (3 and 4) there was no SPAS motion detected immediately after firing the forward RCS jet. But when AUTO DAP was reselected in both cases, the resultant aft RCS jet firings caused SPAS rotations and translations that were easily apparent.

After data point 4 was taken, the subsequent AUTO DAP selection and subsequent aft jet firings resulted in a 1.94 deg/s rotation of SPAS as monitored on the CRT telemetry. While SPAS was aft, it became apparent that the TV tilt-angle data was giving erroneous range information. Another attempt was made to lock on the RR, and this was successful (slant range ~120 feet). From radar data, it was apparent that the aft RCS plume impingement had caused SPAS translation away from Challenger. The RCS fuel budget was in good shape, and there was no hesitation to reclose to 100 feet as the Orbiter was translated aft to place SPAS over the COAS in preparation for data point 5.

After taking this data point, even greater care was taken to stabilize the Orbiter/SPAS relative position in preparation for the simulated out-of-plane data point, in order to minimize relative transition during this period when visual position monitoring was not as precise. The universal pointing display was used to input a 30° roll angle and the Orbiter was rotated at 0.5 deg/s to the test position. After this test point and the subsequent Orbiter rotation back to -X LVLH attitude, it was noticed that there was about a 10- to 20-foot relative drift (SPAS aft). This was easily corrected and the remaining 150 feet and 200 feet data points were taken. During all of the data points, care was taken to observe the preflight agreed-upon positioning limits of +10° from reticle center while taking points 1, 2, 5, 7, and 8.

Jet pulse durations for the test had been sized to produce SPAS ROT's of ~0.15 deg/s. Preliminary data from SPAS indicated that the jet plume characteristics had been well modeled prior to the flight. This gave NASA engineers increased confidence that the jet plume sphere of influence would be well understood in sufficient time to incorporate even more accurate models in simulations that led up to the S M repair mission.

The plume data take was completed prior to the next sunset and the DAP was configured for the 200-foot stationkeeping tasks. Translation pulse sizes of 0.05 and 0.01 ft/s were available in DAP's A and B, respectively, with both DAP's loaded with attitude DB's of 2.0° and 0.5° for NORM and VERN jets, respectively. Low Z mode was not used for stationkeeping. The stationkeeping task was easily accomplished with range (R) and range rate (R-DOT) from the RR provided on the digital displays. Elevation and azimuth were generally monitored visually through the COAS. Stationkeeping was easily accomplished during the 45 minutes allotted, with relatively few Orbiter inputs required. Generally, DAP B was selected to make use of the small (0.01 ft/s) pulse size. Cycling between NORM and VERN jets permitted use of the small VERN attitude DB to resolve visual position ambiguities between Orbiter attitude and translation (X or Y axis) offsets.

SPAS was commanded to a computed inertial attitude in preparation for the inertial 200-foot fly-around and inertial approach. When properly oriented, the Orbiter MNVR option attitude that would coalign the Orbiter and SPAS axes was entered in the UNIV PTG display. START MNVR was executed, low Z was selected, and the Orbiter rotation rate of 0.15 deg/s was initiated. The pilot made translation commands to maintain SPAS in the COAS and the 120° out-of-plane fly-over was initiated. Initial translation inputs were made using 0.05-ft/s pulses and were easily controlled. At no time did it seem that a response lagged demand, and it is felt a higher ROT rate than 0.15 deg/s would have been possible. Once the translation was initiated, very few inputs were required at all. Range was stable at 200 feet for at least the first 90° of rotation. This suggests that either orbital mechanics effects were negligible, or these effects were compensated by DAP characteristics. After approximately 90° of Orbiter ROT, a closing rate was induced (not intentional), which suggests some DAP or orbital mechanics interaction. As an approach to SPAS was the ultimate goal, +Z inputs were made to keep closing rate less than 0.2 ft/s, but no effort was made to null the rate.

When _Challenger_ had reached the final desired attitude, THC inputs were made to maintain SPAS in the COAS, and thus stop Orbiter translation. This was easily accomplished. _Challenger_ was maintained in inertial attitude hold and desired deceleration braking gates were observed.

Final approach was done with SPAS centered in the COAS. By monitoring SPAS/Orbiter range and range rate by apparent position on the TV monitors (radar lock was lost at 60 feet on the digital display), closing rate was nulled as the SPAS appeared on the RMS wrist camera field of view. Orbiter Y translation was monitored out-the-window, whereas Orbiter translation was monitored both out-the-window and on the arm wrist camera (the EE CCTV) monitor. Orbiter inputs were terminated and command of the arm was turned over to the mission specialist with a small SPAS-forward translation in progress. The grapple was completed without incident.

SUMMARY

The entire day of PROX OPS went extremely well. This was primarily due to the detailed procedural work conducted preflight, excellent handling by the ground of a SPAS thermal problem, and outstanding flight characteristics of both the Orbiter and the SPAS.

In short, the Orbiter proved to be a very responsive vehicle that was straightforward to fly in the vicinity of another satellite, given the proper experience base with ground simulations. Fuel usage corresponded very well with that predicted preflight. The radar worked well at the ranges tested, slightly greater than 1000 feet. The only Orbiter deficiency noted was the lack of capability to light the TGT at ranges greater than 300 feet, which will be required for nighttime stationkeeping on non-illuminated TGT's.

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A report, Ku-Band - The First Year of Operation by J. W. Griffin et al, described one problem on STS-7. "The inertial line-of-sight rate data was not useful to the crew due to large excursions. Although these excursions were predicted before the mission, they represented an out-of-spec condition. Later analysis found that the original analysis had neglected the effects of finite null depth in the monopulse pattern. A finite null depth represents a significant gain reduction at boresight when compared to an assumption of infinite depth. The error caused a low servo gain and the resultant poor rate performance."

B. STS 41-B (STS-11) was launched February 3, 1984/1300 GMT, with a crew of Brand (CDR), Gibson (PLT), McNair (MS1), Stewart (MS2 and EVA2), and McCandless (MS3 and EVA1). One detailed test objective (DTO) involved PROX OPS with an ejected tracking balloon, the integrated RNDZ target (IRT). Planned MNVR's are shown on figure A-4. Due to structural failure in the IRT launch canister, the protective-staves jettison pyro was never initiated following deploy, and the initiation of balloon inflation, while still constrained by metal staves, led to overpressure disintegration of the IRT. An abbreviated set of tests was still conducted.

(Note: After months of negotiating, an IRT had also been manifested on DOD STS-10 mission, but major delay of that mission led to loss of that flight opportunity. See figure A-3.)

The DA8 "lessons learned" reported that

- STRK and radar sensors worked better than specification (no RNDZ due to balloon system debris following explosion).
  - MMU running lights were essential to track the MMU in darkness.

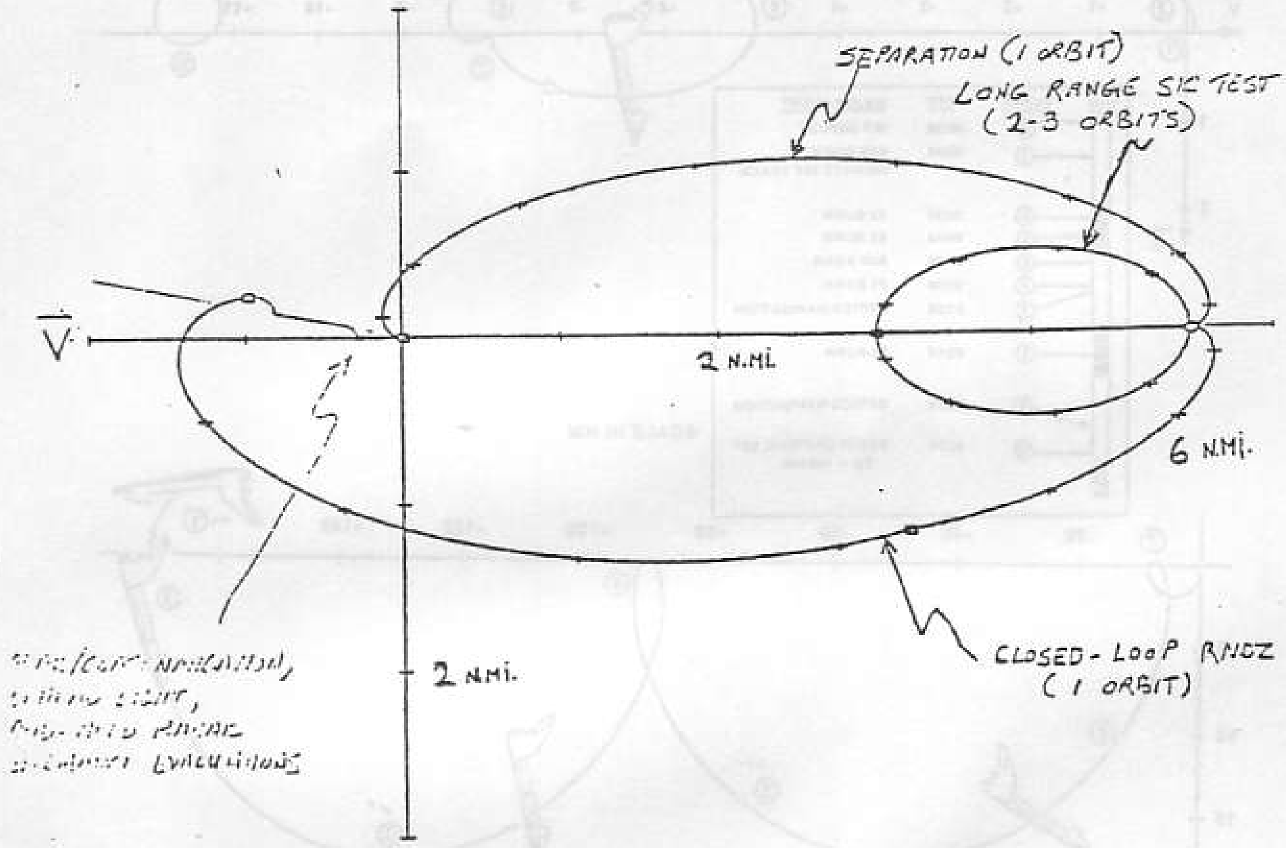


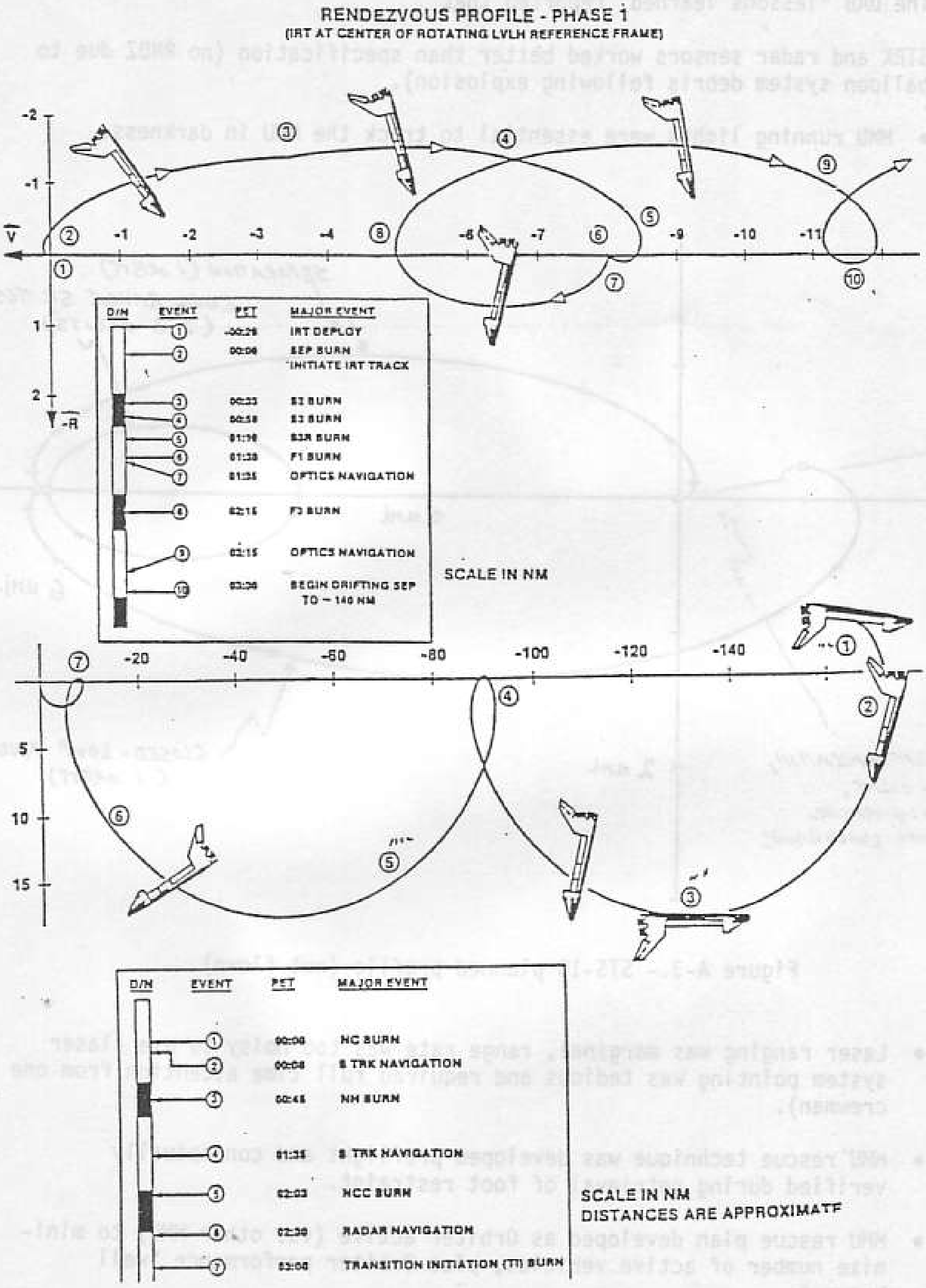
Figure A-3.- STS-10 planned profile (not flown).

- Laser ranging was marginal, range rate was too noisy to use (laser system pointing was tedious and required full time attention from one crewman).

- MMU rescue technique was developed preflight and conceptually verified during retrieval of foot restraint.

- MMU rescue plan developed as Orbiter active (vs. other MMU) to minimize number of active vehicles, plus Orbiter performance "well known."

- Breakout MNVR executed in response to balloon system explosion, to assure Orbiter/TGT balloon did not come into contact.



RENDEZVOUS PROFILE - PHASE 1

(IRT AT CENTER OF ROTATING LVLH REFERENCE FRAME)

D/N	EVENT	PET	MAJOR EVENT
	①	-00:29	IRT DEPLOY
	②	00:06	SEP BURN INITIATE IRT TRACK
	③	00:33	S2 BURN
	④	00:58	S3 BURN
	⑤	01:16	S3R BURN
	⑥	01:30	F1 BURN
	⑦	01:35	OPTICS NAVIGATION
	⑧	02:15	F3 BURN
	⑨	03:15	OPTICS NAVIGATION
	⑩	03:36	BEGIN DRIFTING SEP TO ~ 140 NM

D/N	EVENT	PET	MAJOR EVENT
	①	00:06	NC BURN
	②	00:06	S TRK NAVIGATION
	③	00:45	NH BURN
	④	01:35	S TRK NAVIGATION
	⑤	02:03	NCC BURN
	⑥	02:30	RADAR NAVIGATION
	⑦	03:06	TRANSITION INITIATION (TI) BURN

Figure A-4.- STS-11 Rendezvous profile (IRT at center of rotating reference frame).

C. STS 41-C (STS-13) was launched April 6, 1984/1358 GMT, with a crew of Crippen (CDR), Scobee (PLT), Hart (MS1), Van Hoften (MS2), and Nelson (MS3). The crew deployed the LDEF satellite, and then performed two RNDZ's with the disabled Solar Maximum satellite, capturing and repairing it on the second attempt. This was the first Shuttle Orbiter RNDZ. The planned and actual SMM RNDZ profiles are shown in figures A-5 and A-6.

The DA8 "lessons learned" list included

- Spacecraft (SMM) was highly visible and was picked up in STRK early in RNDZ (~200 n. mi.).
- STRK passes were occasionally very noisy due to small differences in inertial measurement-unit midvalue-select routine in GPC software.
- Forward RCS fuel savings techniques were developed for second RNDZ attempt (MNVR to attitude using tail-only PRCS, delete multiaxis burns where possible, hold attitude on VRCS).
- Breakout MNVR strategy developed for all points along RNDZ and PROX OPS trajectory to assure unplanned contact does not occur. Breakout implemented at end of first capture attempt.
- Orbiter separation from spacecraft after first RNDZ occurred faster than planned. Problem had previously been suspected/observed and is still under analysis. Suspect orbital energy growth due to Orbiter plume impingement/scarfing during attitude control pulses with VRCS.
- Orbiter plume effects can be significant (surface area and orientation dependent) even when spacecraft is in quiet zone.
- Orbiter translations and ROT's using low Z mode use up to 12 times amount of ideal propellant; low Z only effective for single Z axis braking and must be used judiciously.
- Orbiter active MMU rescue analyzed preflight and found to be very costly for three bodies (avoid collision, keep view of satellite) resulting in relatively high propellant budget to allow MMU free flight (about three times alone).

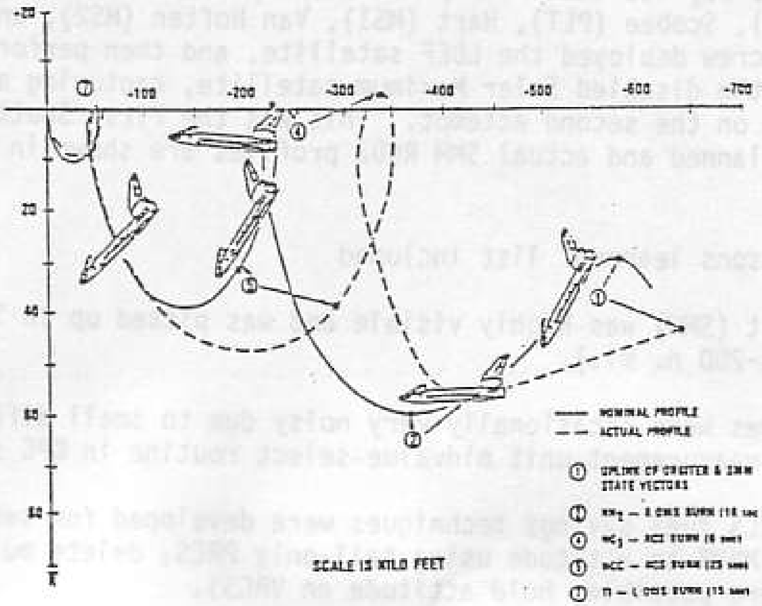


Figure A-5.- SMRM rendezvous.

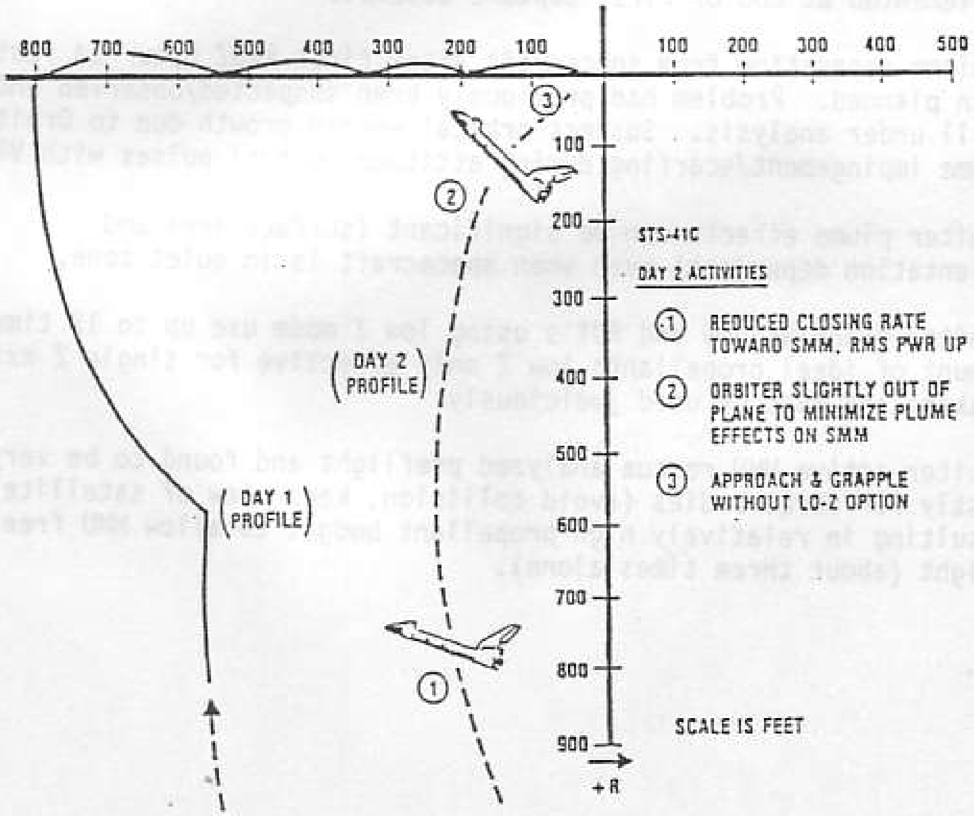


Figure A-6.- SMRM final approach 1 and 2.

The 41-C flightcrew report made these comments on RNDZ operations.

LDEF

The release and separation of LDEF were nominal in all respects. The end effector mode was entered, and the Orbiter was placed in free drift about 2 minutes before the release. The first few inches of RMS motion after the release were done with vernier rates and a minimum THC input. During the 3 minutes following the release, no relative motion was observed using the trunnion pin overlay on the CCTV monitor. The 0.5 ft/s posigrade separation rate was verified by radar at about 100 feet, and the laser range finders tracked to about 200 feet.

The REL NAV function was used with the radar as its input. At about 300 feet, several radar angle marks were rejected with a residual of about 4°. It seemed that the likely cause at this close range was a shift of the tracking from one point of the LDEF to another as the aspect angle changed. At about 1200 feet the Ku mode was changed to GPC. The radar broke track momentarily and then reacquired with angle residual of about 7°. The bad angles were rejected until AUTO track was reestablished at about 1800 feet. The bad angle data appeared to have been caused by a sidelobe tracking the TGT. Radar TRK was discontinued at 2800 feet. At 25,000 feet, radar acquisition in GPC was attempted with the Orbiter in -ZLV, nose forward. TGT track was immediate and the REL NAV performed nominally until the radar track was discontinued at about 35,000 feet.

RENDEZVOUS

The onboard-RNDZ phase began on day 3, 1 hour before the NH burn, and ended at the V-BAR stationkeeping with the initiation of proximity operations. A second RNDZ on day 5 was completed using similar procedures without the need for an NH burn. In order to conserve propellant on day 5, all of the attitude maneuvers were done in vernier reaction control system (VRCS) at 0.2 deg/s, instead of the nominal 0.5 on PRCS.

The first STRK pass began at about orbital noon, three REV's before the rendezvous. The -Z STRK initially began tracking a star that was several degrees from the predicted LOS to the TGT. A BREAK TRACK was commanded and the TGT was acquired on the next attempt. The initial residuals were small, but were randomly changing by more than the 0.05° limit per NAV cycle. AUTO editing was selected since the residuals seemed to be centered on the TGT. The FILTER MINUS PROP (F-P) parameter varied between 1 and 4 kft in response to the noisy data, and the STRK pass ended with 173 marks and an F-P of 1 kft. The TGT was barely visible 10 minutes after orbital noon and could be marked with the COAS at 20 minutes. The range residual was approximately 600 kft.

The second STRK pass occurred at about 250 kft and had similarly noisy data at times. It ended with 152 marks and an F-P of 5 kft. By contrast, the -Z STRK showed no noise during either pass of the day 5

RNDZ. With 155 marks on the first pass and 101 on the second, the day 5 F-P's were 2 kft and 1 kft. The only day-5 STRK anomaly occurred when a piece of ice, visible in the COAS, caused the STRK to temporarily break track with the TGT. The angles were rejected for two NAV cycles, and the TGT was automatically reacquired.

The radar failed self-test with a "333.3" signature as it had several times earlier in the mission. The MCC reported that the failure was caused by unexplained noise and that there was no degradation in the radar. One curiosity was noticed on the REL NAV display at the conclusion of the self-test. REL NAV has interpreted the self-test as data and computed the residuals based on a range and range rate of "333.3". This phenomenon had not been observed in any simulation and care was taken not to allow the data into the filter.

On each RNDZ the radar initially began tracking at about 114 kft, broke track, and reacquired at about 104 kft. The initial range residual was 1.8 kft on day 3, and 0.5 kft on day 5. The radar track was solid in range, range rate, and angles. At the suggestion of the MCC, radar angles were selected instead of the third STRK pass on both day 3 and day 5.

Throughout training, and during each RNDZ, the downrange position of the transition initiate MNVR was observed to increase from the nominal -48 kft target to as far as -58 kft on day 3. The resulting trajectory on day 3 was greater than 3-sigma long. Typically, the NCC burn would be trimmed to within 0.2 ft/s in each axis, and a preliminary targeting of Ti would confirm that the burn had hit the -48 kft TGT within 1 kft. As the intermediate and final solutions were computed with little or no radar updates to NAV, the trajectory would gradually become longer. The day-5 trajectory was at -52 kft, between 1- and 2-sigma long. This phenomenon of the range to the TGT increasing as compared to the predicted range, seemed to continue after Ti. The first two midcourse burns on both day 3 and day 5 were 1 to 2 ft/s radially toward the Earth, indicating that the range to the TGT was greater than the range predicted immediately after the preceding burn. In each case, the TIG slip of the elevation burn MC2 was near, or slightly beyond, the 5-minute limit.

The final two midcourse burns were small on both day 3 and day 5, and the trajectory was nominal from sunrise through the manual trajectory control phase. No pointing errors were evident at sunrise, and an inertial attitude was established at the nominal time of MC2 + 22:00. Very few THC inputs were required to maintain the inertial line of sight. At 2000 feet, the range rate was about 7.5 ft/s, and the initial braking was done to reduce it to 4 ft/s. At 1500 feet, some additional braking was required to meet the 2 ft/s gate. On day 3, the closure was stopped at 800 feet, and the V-BAR was established before orbital noon. On day 5, the closure rate was maintained to conserve FRCS propellant. This resulted in reaching the V-BAR at 350 feet. This type of approach is recommended for future RNDZ.

The backup techniques for determining range and range rate during the manual trajectory-control phase required the use of overlays on a CCTV monitor. This technique would not have been usable because of the inability of the CCTV ALC loop to regulate on a small brightly-lighted target against a black background. Manual control of the iris may have helped, if time had permitted. Ranging by measuring the subtended angle of the TGT in the COAS is probably adequate for trajectories that are not badly dispersed.

PROXIMITY OPERATIONS

On the initial approach to the Solar Maximum satellite, the Orbiter was slowed to 0.2 ft/s at 250 feet. Low Z was selected at 200 feet. Final braking was initiated with the intent of parking the Orbiter between 150 and 200 feet on the V-BAR, and stationkeeping during the orbit night phase. At this time, the Solar Maximum satellite was approximately 2° high in the COAS. The closure rate could be eliminated, but within a very short time the attitude corrections, which were automatically responding to DB excursions, would reinitiate a closure rate of 0.2 ft/s.

Attitude control was maintained with NORM jets during this period, because VERN jets had demonstrated a similar closure problem in simulations. Preflight simulation had also randomly demonstrated this closure problem with low Z NORM jets, but not to the degree experienced during flight.

Range continued to decrease, and extreme jet braking activity proved ineffective in stopping the closure rate. Finally, at 80 feet, the Solar Maximum satellite was moved to 8° high in the COAS to try to use the orbital mechanics effect of having the Orbiter c.g. well below the Solar Maximum satellite to produce an opening rate. This worked with some degree of success, and the Orbiter was backed out of 140 feet. However, the closure rate started again at the very slow rate. As a result of this exercise, the low Z control mode was not considered a viable stationkeeping mode.

With the Orbiter lighting configuration, 250 feet was considered the maximum stationkeeping distance during orbital night. For some payloads, 250 feet may be too close for NORM jet activity without low Z. If a requirement exists to station keep during night periods outside of 250 feet, better Orbiter exterior lighting should be provided, or stationkeeping may not be a viable option. It should also be pointed out that lighting was adequate for a comfortable approach and grapple during the orbital night period as long as the range was less than 250 feet at sunset.

Trajectories with low beta angles, where the path of the Sun comes very close to the TGT, which was the case for the Solar Maximum satellite, were a difficult visual situation. It was important during stationkeeping to be in as stable a situation as possible because it was extremely painful to try to observe the TGT with the Sun in the crews' eyes. The radar range and range rate helped for the opening/closing rates, but the LOS meter was too noisy to be useful, hence there was no reasonable way to make up for the loss of visual tracking for up/down and left/right motion.

For the RNDZ, the final approach was made with no intent to station keep. The Orbiter was again slowed to 0.2 ft/s at 250 feet on the V-BAR and low Z was selected at 200 feet. To avoid the Sun interference problem, inertial attitude hold was selected about 15° earlier than the "end-on" approach that had been practiced in simulations for rotating grapples. This totally eliminated the Sun problem and proved not to hamper the grapple operations.

To ensure proper braking, low Z was deselected at approximately 80 feet with the Solar Maximum satellite over the PLB where plume impingement did not appear to be a problem. A small amount of rippling of the Mylar on the satellite was noted, but no attitude changes were observed due to jet firings. The Solar Maximum satellite translation was stopped when it was in the RMS wrist camera field of view for the grapple attempt.

Parking the satellite over the bay for the RMS attempts with a satellite of this size while rotating, even tumbling as it was on the first attempt, was not considered a problem.

* * * *

A detailed account of Ku-band RR performance on STS 41-C was given in Ku-Band - The First Year of Operation, by J. W. Griffin et al. The relevant section says:

Operations for the Ku-band on STS 41-C began 1 hour and 40 minutes after launch with deployment and an initial self test. With the self-test having indicated no problems and no evidence of extraneous TGT's, the system switched to communications mode until just prior to deployment of the long duration exposure facility (LDEF) 25 hours later. Immediately upon switching into radar mode, received signal strength spikes, and false TGT indications (identical to those seen on STS-11) were observed. As a result, two subsequent self-tests failed. Suddenly, 15 minutes prior to the release of LDEF, the indications stopped. Shortly after the release, the radar track signal went high and displays reported 88 feet. As Challenger backed away at 2.0 ft/s, the radar remained in track until 2500 feet when the system was returned to communications mode. An hour and a half later the system was switched back to radar. During a successful self-test, one RSS spike was observed. Minutes later after reconfiguration, the radar achieved reacquisition of LDEF on the first attempt at 25,276 feet, with an opening velocity of 4.5 ft/s. Track continued in excess of 35,000 feet, at which time the system was again returned to communications operations, where it remained for over 6 hours. Immediately upon switching to radar, the false TGT indications returned and two subsequent self-tests failed. Following yet another switch to communications mode, the radar was readied for the Solar Maximum satellite acquisiton with the Kalman filter propagating the relative states.

Acquisition of the Solar Maximum occurred at 101,553 feet. Based upon an estimated RCS of 2.0 square meters, acquisition was expected at 85,000 feet. RSS data throughout the subsequent track to 89 feet showed the Solar Maximum satellite tumbling at 1/6 revolution per minute. Stationkeeping at 100 feet, mission specialist Dr. George Nelson translated the separation distance aboard his MMU and valiantly attempted harnessing the tumbling satellite. Unsuccessful in his attempts, Nelson returned to the Orbiter, and Challenger was backed away overnight.

During the separation, with the Solar Maximum satellite inside the minimum acquisition and distance of 100 feet, the radar was commanded to reacquire. Confusion in the relative position of Challenger and the Solar Maximum satellite, created by the Orbiter's maneuvering to the retrograde burn attitude, caused the initial manual and autotrack acquisition attempts to fail. Within seconds upon switching to GPC acquisition, the radar found the Solar Maximum satellite at 5298 feet, and continued to track to 54,000 feet when the system was reverted to communication mode.

With one exception, the second Solar Maximum RNDZ was almost a duplicate of the first, displaced by 48 hours, with acquisition at 110,000 feet and break track at 88 feet. At 54,555 feet, the radar reported an ambiguous velocity of 114 ft/s instead of the correct velocity of 8 ft/s. Subsequent data analysis showed the anomalous reading to be a result of a TGT fade. A reasonability check of the Kalman filter correctly rejected the mark. Mission specialist Terry Hart successfully grappled the Solar Maximum satellite with the RMS almost exactly 4 days into the mission. Two minutes later, Ku-band returned to COMM to provide the world with television coverage of the initial inspection within the payload bay.

On flight day 6, after the Solar Maximum satellite repair and yet another failed self-test, the radar was able to acquire the satellite at 198 feet as Challenger backed away, in spite of many false TGT indications. Track was maintained to 680 feet where the antenna reached a position that indicated it was about to illuminate the payload, which turns off the transmitter. Following some spikes on the RF power monitor and an unsuccessful attempt to reacquire because the antenna was pointed away from the TGT, the system returned to communications until flight day 7. Believing the apparent interference to be aboard the Orbiter, an attempt was made to locate a source on flight day 7. During the test, four self-tests were performed with three failing in the presence of false TGT's. Also during the test, the S-band communications system was reconfigured along with switching several elements that input to both S-band and Ku-band. In all configurations the false signals were present. After the mission, similar interference tests were conducted at the Orbiter Processing Facility of the Kennedy Space Center, using many other elements of the Orbiter. Under no conditions were false signals like those seen on orbit reproduced. As of the date of this writing, the source of interference has not been located.

TABLE A-2.- STS 41-C MANEUVER SUMMARY

MNVR thrusters	TIG (MET) Planned Executed	ΔVTOT (FPS) Planned Executed	PEG 7 ΔVX (FPS) Planned Executed	PEG 7 ΔVY (FPS) Planned Executed	PEG 7 ΔVZ (FPS) Planned Executed	HA X HP (NM)
OMS-2 Both OMS	0/00:42:56.1 *	149.0 *	148.9 *	3.0 *	2.1 *	252 X 115
NC1 OMS left	0/05:17:57.7 0/05:17:57.7	11.3 11.4	11.3 11.4	0.0 0.2	0.1 0.2	251 X 121
NPC OMS left	0/06:57:35.4 0/06:57:35.4	9.3 9.4	0.0 0.0	9.3 9.4	0.0 0.1	251 X 121
NH2 OMS right	0/22:50:09.4 0/22:50:09.4	11.7 11.8	11.7 11.8	0.0 0.1	0.1 0.0	258 X 122
NSR Both OMS	0/23:34:53.0 0/23:34:53.0	231.0 231.1	230.5 230.6	0.0 0.0	15.4 15.4	258 X 255
LDEF SEP RCS + Z	1/03:25:00.0 1/03:25:00.0	0.5 0.5	0.5 0.4	0.0 0.0	-0.1 -0.2	259 X 255
NC2 RCS + X	1/07:40:01.1 1/07:40:01.1	1.5 1.5	1.5 1.5	0.0 0.0	0.0 0.0	259 X 256
NH2 OMS right	1/20:13:37.7 1/20:13:37.7	14.1 14.2	14.1 14.2	0.0 -0.1	0.1 0.2	266 X 258
NC3 Multiaxis	1/21:00:54.9 1/21:00:54.9	0.3 0.2	0.3 0.2	0.0 0.1	0.0 0.0	267 X 258
NCC Multiaxis	1/21:36:12.4 1/21:36:12.4	0.7 0.7	-0.2 0.1	0.0 0.1	0.7 0.7	267 X 258
TI OMS left	1/22:35:19.0 1/22:35:19.0	11.4 11.5	11.3 11.4	-1.1 -1.1	-1.3 -1.4	268 X 264
MC1 Multiaxis	1/23:01:25.0 1/23:01:25.0	* 1.0	* -0.3	* -0.1	* 0.9	*
PLANE NULL	NOT EXECUTED					
MC2 Multiaxis	1/23:30:55.0 1/23:30:55.0	* *	* *	* *	* *	*
MC3 Multiaxis	1/23:40:55.0 1/23:40:55.0	 *	* *	* *	* *	*
MC4 Multiaxis	1/23:50:55.0 1/23:50:55.0	0.1	0.1	0.0	0.0	*
Proximity operations						

*Data not available.

TABLE A-2.- Concluded

MNVR thrusters	TIG (MET) Planned executed	ΔVTOT (FPS) Planned executed	PEG 7 ΔVX (FPS) Planned executed	PEG 7 ΔVY (FPS) Planned executed	PEG 7 ΔVZ (FPS) Planned executed	HA X HP (NM)
SMM SEP 1 RCS + X	2/02:40:00 *	0.5 *	0.0 *	0.0 *	-0.5 *	*
SMM SEP 2 Multiaxis	2/02:50:00	0.8 *	0.8 *	0.0 *	0.0 *	*
NC4 RCS + X	2/17:03:55.2 2/17:03:55.2	2.5 2.4	-2.5 -2.4	0.0 0.0	0.0 -0.1	268 X 265
NC5 RCS + X	3/04:30:00.0 3/04:30:00.0	2.3 2.1	-2.3 -2.1	0.0 0.0	0.0 0.1	268 X 264
Start of second rendezvous						
NC6 OMS right	3/18:40:05.3 3/18:40:05.3	7.6 8.0	-7.6 -8.0	0.0 0.1	0.0 0.1	268 X 261
NCC Multiaxis	3/20:49:56.4 3/20:49:56.4	1.1 1.3	-1.1 -1.3	0.1 0.1	0.0 0.1	267 X 261
TI OMS left	3/21:49:03.0 3/21:49:03.0	5.6 5.8	5.6 5.8	0.1 0.1	-0.3 -0.6	268 X 264
MC1 Multiaxis	3/22:15:09.0 *	0.9 *	-0.3 *	0.0 *	0.9 *	*
MC2 Multiaxis	3/22:45:12.0 *	0.7 *	-0.3 *	-0.1 *	-0.6 *	*
MC3 Multiaxis	3/22:55:12.0 *	0.6 *	-0.4 *	-0.1 *	-0.4 *	*
MC4 Multiaxis	3/23:05:12.0 *	0.3 *	-0.3 *	-0.1 *	-0.1 *	
Proximity operations						
FSS test RCS + X	4/18:45:00.0 4/18:45:00.0	1.0 0.9	1.0 0.9	0.0 0.0	0.0 0.0	269 X 265
SMM SEP 1 Multiaxis	* 5/20:04:50.0	1.0 1.2	-0.2 -0.2	0.0 0.0	1.0 1.2	269 X 265
SMM SEP 2 Multiaxis	* 5/20:34:50.0	2.0 1.9	-2.0 -1.9	0.0 0.0	0.0 0.2	268 X 264
Deorbit BOTH OMS	6/22:31:30.0 6/22:31:30.0	460.4 460.8	-393.5 -393.5	0.0 -1.1	-239.0 -239.7	271 X 0

*Data not available.

D. STS 51-A was launched November 8, 1986/1215 GMT, with a crew of Hauck (CDR), Walker (PLT), Allen (MS1), Fisher, A. (MS2), and Gardner (MS3). After deploying two PAM-D payloads, the crew twice rendezvoused with PAM-D payloads (the Palapa and Westar) left in low orbits by injection failures following deployment from STS 41-B in February.

RNDZ profile is shown in figure A-7.

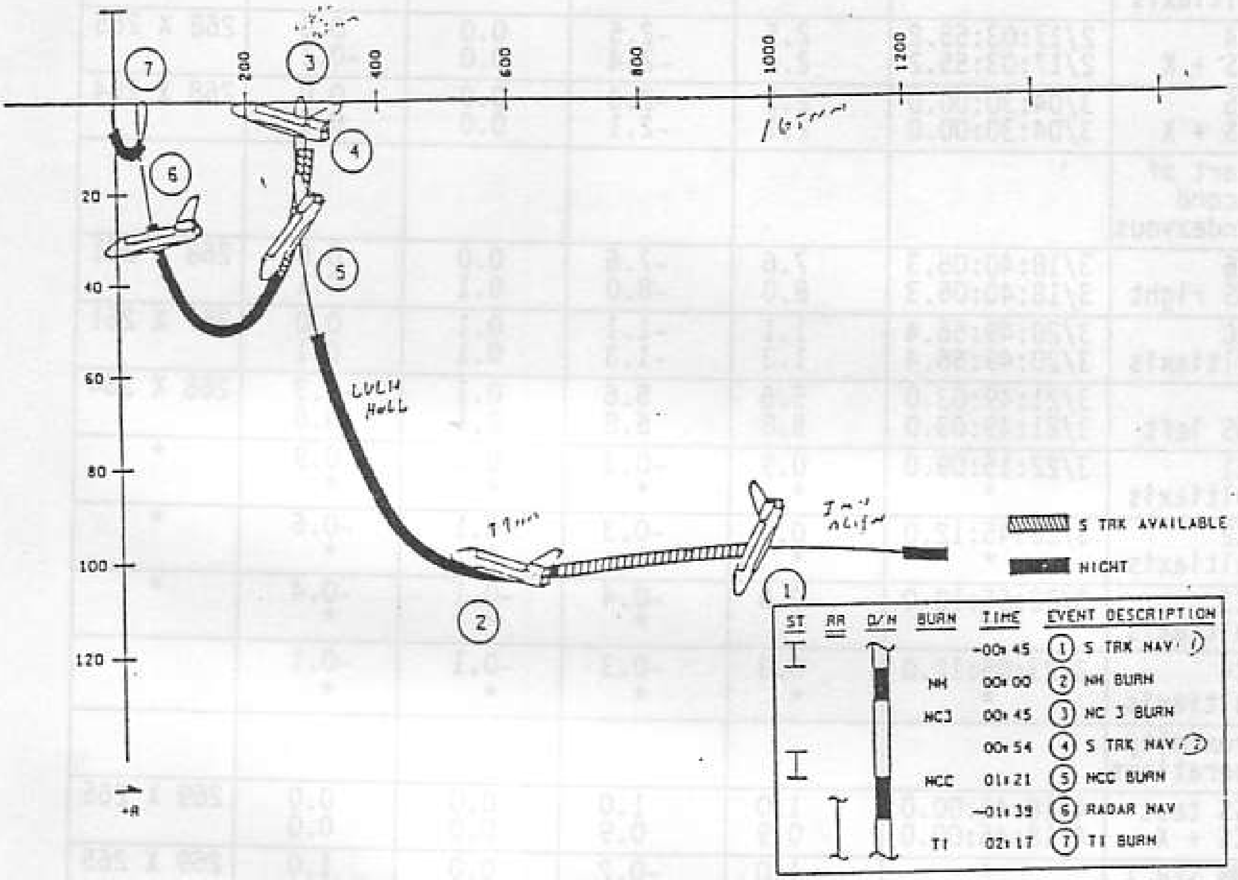


Figure A-7.- 51-A First RNDZ.

The DA8 "lessons learned" highlights these items.

- Spacecraft visibility was better than predicted. They were picked up in STRK at >100 n. mi. (used -Y tracker for first time).
- Deselect one IMU for STRK passes did smooth data.
- Stationkeeping at 35 feet eliminated plume disturbance concern. Used "normal" PRCS mode for translation adjustments. Used "low Z" mode from 200 feet to 35 feet. Did not use "low Z" for stationkeeping.

GENERAL

- Two deployables, two RNDZ's. These were unique RNDZ's since both satellites had to be deboosted from a higher orbit of different inclination. A phantom box was created for the RNDZ with the Orbiter and each satellite.
- Variable OMS-2 targeted to a phase angle at the circularization MNVR. The circularization MNVR was an arbitrary choice since there were more than 10 MNVR's between OMS-2 and NC3.
- NC1 biased posigrade (10 ft/s) for insertion dispersions.
- Circularize orbit morning of FD 2 for deployables.
- Backup separation burn was biased posigrade (6 ft/s) to ensure an adequate separation. Only two separation burns would be done; the third would be a phasing burn. Thus, the phasing burn could occur before or after either separation burn.

PALAPA RENDEZVOUS

- NPC scheduled sometime the afternoon of FD 3.
- NSR included to set lighting for terminal phase.
- NC2 biased posigrade (2 ft/s) to prevent going retrograde.
- Typical NH, NC, one-REV transfer to Ti. One-REV transfer to Ti dictated by the EVA requirement (crew workday).
- STRK pass prior to NH was questionable, due to acquisition range. This had the potential to be a one STRK RNDZ.

WESTAR RENDEZVOUS

- One-REV transfer to Ti. Again, this was an EVA constraint (crew workday).
- There was a potential for freezing of the fuel remaining in Palapa, which was an automatic jettison case. To prevent this from happening, used the -Y STRK in a generally Sun-facing attitude for STRK pass 1 (prior to NH). If additional Sun was required to keep Palapa warm, STRK pass 2 would be done with the -Y STRK. If even more Sun was needed, a Ti delay would be executed with the Orbiter in a solar inertial attitude. This was a very difficult thermal problem since the PAM ASE's could not be overheated.

- Westar and Palapa were supposed to be coplanar; they were not. We were lucky and were able to combine NC1-2 and NPC-2 (unscheduled MNVR) together and save fuel.

* * * *

The STS 51-A flightcrew report (March 28, 1985) made the following comments on RNDZ:

RENDEZVOUS

Crew Responsibilities

Because the PLT was to be very busy during the RNDZ MNVR's as the IV1 crewman (assisting the EVA crewmen in suit donning and checkout), the MS2 was assigned prime responsibility for assisting the CDR in executing the MNVR's. The CDR and MS2 had worked closely with the PROX OPS book procedures writer and felt very comfortable with the book. From the beginning of training it was baselined (as with all procedures which used on-orbit OMS or RCS fuel) that all MNVR's and burns would be set up and checked by two crewmembers. All of the 44 OMS and RCS MNVR's involved in RNDZ were executed this way with virtually no errors.

The OMS burns are single-axis burns performed under GPC control after a GPC-controlled maneuver to burn attitude. However, the RCS burns are primarily multiaxis burns which require manual inputs to the THC and are therefore more susceptible to errors in execution and slightly less efficient than automatic burns would be.

Recommendation: Incorporate in future software the capability to perform GPC-controlled RCS burns.

In OPS 201 the UNIV PTG display provides a maneuver completion time for all attitude maneuvers. In OPS 202 (the OPS mode for on-orbit burns) this information is not available. The crew was often concerned about initiating maneuvers to burn attitude early enough. The potential exists, due to the lack of data regarding maneuver completion time, that a more RCS-expensive maneuver mode (NORM vs. VERN), or rate, could be used by the crew for "insurance."

Recommendation: Incorporate maneuver completion time on the OPS 202 MNVR EXEC display.

STAR TRACKERS (STRK)

The STRK performance was excellent. All four attempts (two per RNDZ) at acquiring the satellites were successful at ranges of up to 120 miles. For each STRK pass, IMU3 was deselected to avoid the selection of filter-induced noise on the data which had occurred on STS 41-C. For the second STRK pass on each RNDZ, the STRK shutter had to be manually opened.

RENDEZVOUS RADAR (RR)

The RR performance was also excellent. Initial and solid lock-on for Palapa was 136 kft. Initial Westar lock-on occurred at 130 kft with solid lock-on at 120 kft. Good RR data was essential for mission success. Preflight data indicated that RR failure prior to first RNDZ associated with significant dispersions would have resulted in insufficient FRCS fuel to complete the second RNDZ.

Recommendation: Reevaluate risk to RNDZ mission success imposed by single string RR and non-interconnectable FRCS system.

Range rate and angular rate data were all smoother (less noisy) than that modeled in the SES.

Recommendation: Use flight data to improve the modeling of range rate and angular rate data in the SES.

TARGET VISIBILITY

Significant time and effort were spent in flight techniques meetings to determine the inertial attitude for the satellites to optimize the trade-off between STRK, RR, and visual acquisition. Worst case estimates were that the satellites might not be visible at 1 mile, the approximate range of the "manual" phase of RNDZ. The final decision was to optimize for STRK acquisition.

In fact, in this attitude the satellites were visible to the eye (acquired with the assistance of the COAS) at over 100 miles.

Recommendation: Feed back flight experience to update analytical models regarding visual acquisition of satellites.

MANUAL PHASE

The RNDZ manual phase begins at orbital sunrise when the TGT is around 1 n. mi. distant. It is the point at which the CDR begins to make manual control inputs to the THC and RHC to ensure Orbiter intercept of the extension of the TGT V-BAR 300 to 400 feet ahead of the TGT with reasonable closure rates. With good RR information, this phase was completed without incident per the published procedures.

PROXIMITY OPERATIONS PHASE

After arrival on the V-BAR, subsequent braking MNVR's were performed as published. On both approaches low Z mode was selected on the DAP at a 250- to 270-foot distance to avoid pluming the satellite with the upward firing jets of the Orbiter. This mode uses approximately nine times the fuel for +Z (or braking) MNVR's than when not in low Z, and thus use of +Z inputs to the THC were minimized during this period. On the first RNDZ (Palapa), several out-of-plane (+ or -Y) inputs were made while in low Z mode to correct a lateral offset (10 to 15 feet to port), which would have brought the RMS too close to the satellite. Shortly thereafter the closure rate was observed to increase from the planned 0.2 ft/s to 0.5 ft/s. After using +Z low Z firings to bring closure rate back to 0.2 ft/s, a subsequent increase in closure rate was again observed and then compensated for. Previous flight results have suggested that the firing of Y jets while in low Z may cause a resultant increase in net propulsive effect in the minus Z direction. The flight results tend to confirm that theory. On the second (Westar) RNDZ, the use of Y inputs during low Z operations was minimized and the -Z acceleration effect was not observed.

Recommendation: Analyze the normal jet firing history and RR data to attempt to establish the source of the undesirable -Z acceleration during low Z maneuvering.

Upon reaching 60 to 70 feet separation from the TGT's (at about the same time RR broke lock), low Z mode was deselected, and final braking to the 35-foot stationkeeping position was effected. Both RNDZ profiles resulted in attaining a stationkeeping position approximately 5 minutes past the preplanned time, orbital noon. This did not cause problems since all of the other procedures were nominal and the timing was not critical.

Recommendation: When tracking data indicates that RNDZ dynamics will result in late arrival in the stationkeeping position, and if Sun angle is critical to establishing that position, procedures should be available to adjust the braking gates to compensate.

STATIONKEEPING

Early in the development of the retrieval mission, the fact that the HS 376 satellites are unlit and have limited high-reflectivity surface caused concern about nighttime stationkeeping at 200 feet, which had been baselined on the two previous missions involving stationkeeping. Parallel efforts were initiated to provide enhanced lighting from the Orbiter as well as to investigate close-in stationkeeping. The lighting effort resulted in the manifesting of the Streamlight One Million (1 million candlepower) handheld spotlight, which showed the greatest promise of providing adequate illumination from inside the Orbiter.

Concerns for beam width, light mounting, Orbiter deadbanding, and TV capability as they related to night stationkeeping were in work when the close-in stationkeeping option was adopted, relieving most of those concerns. Issues which were resolved in favor of close-in stationkeeping included:

- Orbiter-to-satellite plume effects
- Stationkeeping RCS usage
- MMU rescue (three body)
- MMU fuel usage

Detailed discussion of these issues may be found in the the STS 51-A Orbit Flight Techniques minutes.

Baselined stationkeeping position was 35 feet from sill to satellite, centered over the bay in Y, approximately 20 feet aft of the forward bulkhead. The RMS was positioned so as to center the satellite in the (+Y axis viewing) wrist camera. Thus the RMS view in the TV monitor gave precise stationkeeping X and Z axis position data, whereas Y axis position was judged by viewing out the overhead window. In flight, the positioning task was well represented by the SES and SMS simulations.

Fuel consumption was somewhat higher during the Palapa retrieval than predicted, and is attributed to two factors:

- The CDR "gains" were a bit high.
- The 3 1/2-foot long OMNI antenna on top of the HS 376 had not been modeled during simulations. When the LVLH attitude of the Orbiter rotated relative to the inertial attitude of the satellite, the volume swept out of the antenna crowded the EVA crewmember's working volume and necessitated the translation of the Orbiter 3 to 5 feet farther (in Z) from the satellites.

Both of the factors were compensated for during the Westar stationkeeping and the RCS usage figures for that period of time should be considered "best case."

Recommendation: Use flight data from the Westar stationkeeping as a baseline for fuel usage for similar stationkeeping projections.

* * * *

A detailed discussion of the required close-in night stationkeeping techniques for 51-A was presented in Space Salvage: A Report on Shuttle Mission STS 51-A by Hauck and Gardner to the Society of Experimental Test Pilots. An excerpt from pages 5 to 7 follows:

"Night stationkeeping on the HS-376 satellite posed an additional challenge to the flight design. During the first Shuttle formation flying on STS-7, the TGT satellite was equipped with battery-powered running lights. The Orbiter was flown at ranges up to 1000 feet from the satellite. Visual tracking of the satellite at night at these distances was not a problem. During the Solar Maximum satellite repair mission, 300-foot stationkeeping was baselined. Even though the Solar Maximum satellite was not equipped with running lights, the large amount of gold-colored, multilayer insulation provided adequate reflection of Orbiter payload bay lights to permit stationkeeping at 200 feet through the night passes. However, the low reflectivity of the HS-376 satellites when viewed from all aspect angles, except from the top, caused serious concern about the crew's ability to maintain visual contact during night stationkeeping.

To relieve this concern, parallel efforts were initiated: the first, to manifest onboard a high-intensity (1 million candlepower) spotlight, and the second, to investigate the feasibility of stationkeeping at greatly reduced separation. As stated, all previous stationkeeping had been done at distances of 200 feet or greater to preclude disturbing the TGT satellite with reaction control jet plumes. A development effort was initiated to determine the feasibility of conducting long-term (more than 30-minute) stationkeeping with 35-foot lateral separation from Orbiter longeron sill to satellite.

A side benefit which could be realized by this configuration would be that the flight of the MMU to capture the satellite would be of much shorter duration, significant because the MMU cold gas fuel budget did not leave large reserves. But the use of the untethered MMU in close proximity to both the Orbiter and the satellite introduced another potential complication. Concern was expressed about failure modes of the MMU, which would necessitate maneuvering of the Orbiter to either rejoin a dormant MMU, or to chase an MMU which had experienced a failed-on thruster and was thus moving rapidly away from the Orbiter. With the satellite free flying directly adjacent to the envelope of the Orbiter payload bay, it was feared that the Shuttle pilot would be severely restricted in his maneuvering volume, and thus might either collide with the satellite or be unable to rejoin the failed MMU within the limits of the RCS fuel budget."

A series of simulations was initiated to evaluate the implications of these concerns. The flightcrew used the SES, which modeled the RCS jet plume, to evaluate the piloting tasks associated with 35-foot stationkeeping. RCS fuel data were generated for long-term stationkeeping and for a variety of MMU rescue scenarios. At the same time, various analyses were done offline to evaluate the effect of various levels of plume forces on the stability of the rotating satellite. The net results of all of the simulations encouraged the decision to proceed with the close-in (35-foot) stationkeeping for the following reasons:

TABLE A-3.- 51-A SUMMARY

FLIGHT/SIM/TEST ID			DATE		CRB	CONSOLE POSITION		PAGE
TIME	FLIGHT EVENTS/HISTORY/BRIEFING *EXECUTED							
	CY6 RNDZ				RNDZ KC :			
	ΔV_T	ΔVX	ΔVY	ΔVZ	ΔV_T	ΔVX	ΔVY	ΔVZ
OMS-2	176.6	176.6	0	0	*177.1	176.4	7.1	14.4
NC1	10.0	10.0	0	0	*8.9	8.9	-.1	.1
NH	5.8	5.8	0	0	*2.9	2.9	0	0
CIR	13.4	13.3	0	-1.8	*12.8	12.8	0	.2
SEP1	11.1	10.6	0	-3.0	*11.0	10.6	-0.3	-2.8
SEP2	15.0	14.4	0	-4.1	*15.2	14.6	0.3	-4.2
NPC	0	0	0	0	*2.4	0	2.4	0
SEP3	6.0	6.0	0	0	*4.0	4.0	-.0	0
NSR	16.5	14.6	0	7.7	*31.5	30.8	-.1	-6.7
NC2	2.0	2.0	0	0	*2.6	2.6	0	0
NH	27.9	27.9	0	0	*22.5	22.5	-.1	-.3
NC3	14.7	14.7	0	0	*12.0	12.0	-.1	0
TI	11.6	11.6	0.1	-0.2	*9.6	9.5	1.4	0.6
RNDZ 1 TOTAL	310.6				312.5			
NC1-2	15.7	-15.7	0	0	*15.3	-13.9	-6.5	0
NPC-2	0	0	0	0	*0	0	0	0
NC2-2	0	0	0	0	*.2	.2	0	-.1
NH-2	.2	-.2	0	0	*.9	-.9	0	.1
NC3-2	.1	-.1	0	0	*3.6	3.6	0	-.1
TI-2	11.9	11.9	0	-.2	*10.5	7.9	.4	7.0
RNDZ 2 TOTAL	27.9				30.5			
TOTAL	338.5				343.0			

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FLIGHT CONTROLLER'S LOG

* U.S. GOVERNMENT PRINTING OFFICE: 1980-780-010/9139

- Fuel usage for the formation flying task was found to be on the same order as that used for 200-foot stationkeeping. There was, in fact, an added RCS fuel saving of not having to expend energy to stop Orbiter relative motion at 200 feet and then reinitiate the closure rate for final join-up on the mated MMU and satellite.
- The shorter flyover distance for the MMU allowed more time to be spent on the other EVA tasks.
- Rescue of the failed MMU was actually enhanced. All of the MMU operations were conducted close to the Orbiter, and MMU failures were therefore detected more rapidly by the onboard crew. Corrective actions were more quickly transmitted to the MMU pilot (who was often unaware of the MMU failure). Transit distances to the failed MMU were decreased; therefore, orbital mechanics effects on the relative motion of the Orbiter and satellite had less time to propagate. Use of a simple sidestep or pitch-up maneuver by the Orbiter pilot resolved concerns about satellite collision. With a limited number of failure scenarios exercised, Orbiter fuel usage appeared to be less than for the 200-foot stationkeeping task.
- Off-line simulations indicated that by using the standard Orbiter braking profile in to 35 feet, very little energy was transferred to the satellite.

Flight evaluation of the close-in stationkeeping configuration was very positive, with Orbiter fuel usage on the order of preflight predictions. Orbiter RCS plume did not cause any apparent upset to the motion of the satellite.

E. In early 1985, John Cox (DA8) presented this compilation of Orbiter rendezvous and PROX OPS experience to a conference on rendezvous.*

1. RNDZ profile is well behaved. The phasing must accommodate other flight plan activities and be within propellant budgets - hence all profiles will be customized to some extent. Multiple RNDZ considerations imply traffic management in future Space Station/OMV/Orbiter operations.
2. Breakout MNVR planning is necessary. Planning should be based upon propellant quantities available and projected usage to complete the RNDZ sequence, especially once the intercept is initiated. Breakout planning is necessary for future RNDZ activities with Orbiter/Space Station/other satellites/OMV.
3. If PL plays an active role in performing RNDZ/PROX OPS sequence, then it should consider carrying a responsibility to perform a non-RF activated breakout MNVR.
4. Propellant quantity will always be a premium. Orbiter forward RCS is most limiting for PROX OPS.

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* Rendezvous and Proximity Operations Workshop, February 19-22, 1985, Kenneth J. Cox, workshop organizer, NASA Johnson Space Center, Houston.

5. RNDZ operations to date have all had excellent performance from NAV sensors, hence operations appear to be standardized. Failure modes and dispersed trajectory conditions have not yet been encountered.

6. Crew control of payload attitude eases RMS or MMU capture task.

7. PROX OPS will tend to be custom designed for each PL. PL flexibility will go a long way in stabilizing this area (e.g., RMS grapple fixture, hand holds, retractable appendages, cooperative TRK, attitude control capability/maneuverability).

8. Contamination evaluation is required for specific payload and specific PROX OPS technique.

9. Plume disturbance susceptibility of each payload must be well understood for PROX OPS design. If susceptibility is significant, then alternate recovery schemes should be developed.

10. Lighting is a significant factor in completing a RNDZ/PROX OPS sequence. Sunlight (direct or reflected) can blind crewmembers or cause TV cameras to "bloom," etc. Insufficient lighting requires close-in stationkeeping to keep TGT in sight during dark passes.

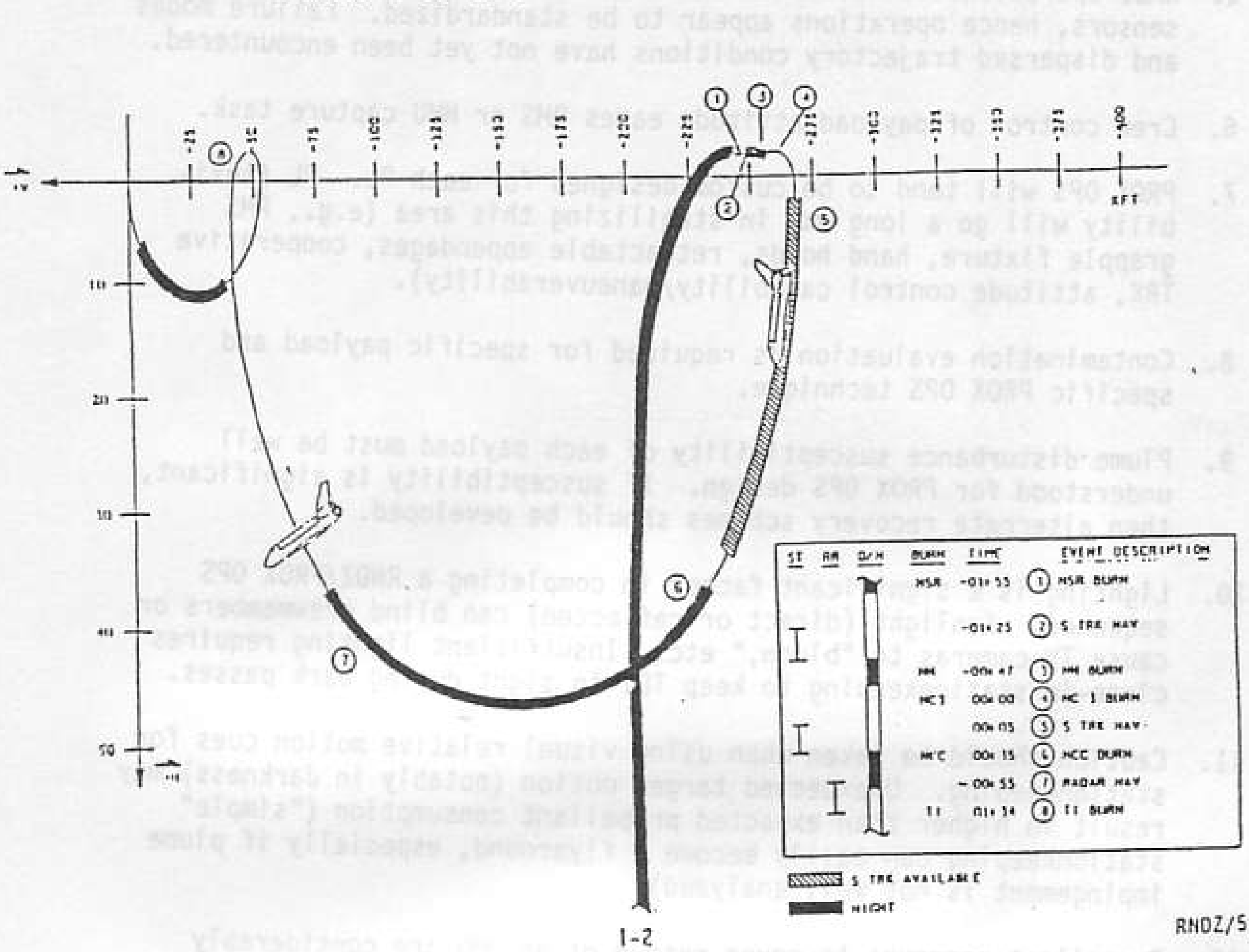
11. Caution should be taken when using visual relative motion cues for stationkeeping. Unexpected target motion (notably in darkness) may result in higher than expected propellant consumption ("simple" stationkeeping can easily become a flyaround, especially if plume impingement is not well analyzed).

12. Propellant reserves to cover rescue of an MMU are considerably higher for the three-body problem (collision avoidance) than for the two-body.

13. Since each retrievable PL will specify different contamination requirements and will offer a variety of profiles, surface areas, and moments of inertia, and will be controlled in attitude and translation by a variety of means, then consideration should be given to providing a flexible retrieve interface that will allow capture by a primary and a backup method. This applies to Orbiter, OMV and Space Station capture activities.

14. Large mass PL's can be man-handled with relative ease, provided the problem has been thought through in advance, and if suitable handholds are available.

15. High fidelity man-in-the-loop simulation is crucial in technique development and operating training.



SI	RR	D/N	BURN	TIME	EVENT DESCRIPTION
			MSR	-01:53	① MSR BURN
				-01:25	② S TRK NAV
			NH	-00:47	③ NH BURN
			NC1	00:00	④ NC 1 BURN
				00:05	⑤ S TRK NAV
			NCC	00:35	⑥ NCC BURN
				-00:55	⑦ RADAR NAV
			TI	01:34	⑧ TI BURN

Figure A-8.- 51-D RNDZ profile.

F. STS 51-D was launched April 12, 1985/1359 GMT with a crew of Bobko (CDR), Williams (PLT), Seddon (MS1), Griggs (MS2 and EVA1), Hoffman (MS3 and EVA2), Walker, C. (PS1), and Garn (PS2). Following deployment, the Syncom F-2 satellite failed, and the crew performed an unplanned RNDZ in an attempt to activate the payload.

The RNDZ profile is shown in figure A-8.

The following comments from the 51-D flightcrew report describe their RNDZ and PROX OPS:

It had been approximately 9 months since the crew completed RNDZ training associated with a SPARTAN PL. The complete cycle of RNDZ and PROX OPS training (about 115 hours of SMS, SES, classroom, RMS), less integrated sims, had been accomplished. No RNDZ or PROX OPS training had been performed since that time. None of the flight data file procedures were onboard.

A rather lengthy teleprinter message was sent up containing most of the nominal RNDZ procedures and cue cards. The crew constructed two FDF RNDZ books using the postinsertion books, the teleprinter message, scissors, and tape. Having a book which looked like the procedures used in previous training was invaluable during conduct of the actual RNDZ. Also, cue cards were constructed, approximating the size and shape of the real cards, using kneeboard cards and Velcro from the IFM kit. These were positioned in their nominal locations.

Fortunately, all of the onboard hardware performed flawlessly. An ST lock-on was obtained prior to going to TGT track. Within three NAV cycles, the angles were very small, and over 100 ST marks were obtained. The RR locked on at approximately 158,000 feet, which seemed to be the maximum number that could be displayed on SPEC 33. Orbit targeting for RNDZ burns was nominal, and the midcourse correction burns were very small, an indication that the NAV states had converged rather well.

RNDZ was performed by the CDR and PLT with MS1 cross-checking and plotting position and velocity on a hand-built graph. This technique had been developed during previous training. The how-goes-it plot maintained by MS1 was very important as a cross-check of targeting.

RNDZ ended with the Orbiter being well-placed for PROX OPS. With no reason to hurry, the approach to the stationkeeping position at 35 feet was done slowly, allowing minimum fuel usage and minimum control inputs. MCC noted that with the approach speed that had been established, closure to 35 feet would not occur before sunset. Closing rate was increased slightly in order to arrive at the 35-foot stationkeeping position by sunset. Low Z DAP was entered at 200 feet, but little change in the closure rate had to be made before the 60-foot point, and little cross-coupling was observed between the attitude control and the closing rate. At 50 feet, normal Z was again selected, and a stationkeeping position was established at 35 feet.

During the final approach phase, which occurred just before going into darkness, the Sun was a significant factor. The sunset was right behind the Syncom, and that made seeing the Syncom difficult and the CCTV useless. Once in the darkness, with the Syncom within 50 feet of the PLB, it was easily seen by the illumination of the PL bay lights, and the CCTV again was a good ranging device. If a RNDZ must be accomplished when the Sun is a factor, provisions for blocking the Sun should be made.

During the night pass, stationkeeping position was easily flown. After going back into sunlight, a flyaround was performed to enable Syncom to be stable with respect to the Orbiter during RMS operations. The flyaround was done using an AUTO MNVR to an inertial attitude with the Syncom still at 35 feet. In the previous Spartan training, the flyaround was performed at 300 feet - just outside the contamination sphere. The 35-foot position was not a difficult procedure, and would have been even easier if it had been practiced during simulations. In the case of this

TABLE A-4 - STS 51-D MANEUVER SUMMARY

MNVR Thruster	TIG (MET) Planned Executed	ΔV_{TOT} (FPS) Planned Executed	PEG 7 ΔV component (ft/s)			HA × HP (NM)
			ΔV_x Planned Executed	ΔV_y Planned Executed	ΔV_z Planned Executed	
OMS-2 Both OMS	0/00:43:21.5 0/00:43:21.5	228.3 228.6	228.2 228.4	0.1 - 1.1	8.4 10.0	249 × 160
SEP-1 Right OMS	0/09:54:25.0 0/09:54:25.0	11.0 11.1	10.6 10.7	0.0 0.2	- 3.0 - 3.0	249 × 167
SEP-2 Both OMS	1/01:14:16.0 1/01:14:16.0	15.0 *	14.4 *	0.0 *	- 4.1 *	250 × .174
Inverse SEP Both OMS	1/02:46:44.4 1/02:46:44.4	15.0 *	- 14.4 *	0.0 *	4.0 *	249 × 167
Phase adjust +Z RCS	1/09:57:00.0 1/09:59:00.0	2.4 2.4	2.4 2.4	0.0 0.0	- 0.0 - 0.3	249 × 167
Phase adjust +Z RCS	3/06:36:00.0 3/06:36:35.0	1.8 1.6	1.8 1.6	0.0 - 0.2	- 0.0 - 0.2	249 × 166
Phase adjust +Z RCS	3/18:54:00.0 3/18:54:00.0	1.7 1.9	1.7 1.9	0.0 - 0.0	0.0 - 0.0	250 × 166
Coelliptic Left OMS	4/06:43:00.0 *	10.8 *	1.2 *	0.0 *	- 10.7 *	249 × 167
NC3 Left OMS	4/19:29:20.0 4/19:29:20.0	11.5 11.6	- 11.5 - 11.6	0.0 0.1	0.0 0.1	243 × 167
NCC Multiaxis	* 4/20:02:42.0	* 0.9	* 0.8	* 0.0	* - 0.4	243 × 167
TI Left OMS	* 4/21:01:30.0	* 8.7	* 8.0	* - 0.6	* - 3.5	247 × 167
MC1 Multiaxis	* 4/21:27:42.0	* 1.4	* - 0.6	* - 0.2	* 1.2	*
Plane null Multiaxis	* 4/21:38:06.0	* 0.2	* 0.0	* - 0.2	* 0.0	*
MC2 Multiaxis	* 4/21:57:26.0	* 1.3	* - 0.6	* - 0.1	* 1.1	*
MC3 Multiaxis	* 4/22:07:26.0	* 0.2	* - 0.2	* - 0.1	* 0.1	*
MC4 Multiaxis	* 4/22:17:26.0	* 0.3	* - 0.1	* 0.1	* - 0.3	*
SEP-3 Low Z	* 5/00:20:07.0	* 0.9	* 0.9	* - 0.0	* - 0.1	249 × 168
SEP-4 Multiaxis	* 5/00:24:00.0	* 1.9	* 0.0	* - 1.9	* - 0.1	249 × 168
SEP-5 Left OMS	* 5/00:39:00.0	* 20.3	* 20.3	* 0.3	* 0.1	249 × 179
Deorbit Both OMS	6/22:45:20.0 6/22:45:20.0	451.5 *	- 279.6 *	320.8 *	-158.8 *	245 × 18

*Data not available.

flyaround, the crew did not know how much time the maneuver would take, or even which way it would go, prior to commencing the maneuver.

Final positioning of the Syncom took longer than expected, since again there was no good "sight picture" from ground simulations. Once the Syncom had been positioned over the starboard longeron, the Orbiter was very stable. No control inputs were made during the first three or four operations with the "fly swatter." The crew was surprised when the motion of the satellite towards the cockpit occurred, caused by the swatter dragging on the Syncom and impacting the lever.

Considering the time since the crew had last trained for RNDZ and PROX OPS, everything went extremely well. Of course, all of the sensors and everything on the Orbiter worked perfectly, but the success of the operation still indicates the training was thorough and the procedures mature.

G. STS 51-G was launched June 17, 1985/1133 GMT, with a crew of Brandenstein (CDR), Creighton (PLT), Lucid (MS1), Nagel (MS2), Fabian (MS3), Baudry (PS1), and al Saud (PS2). After deploying a number of commercial PL's, the crew deployed and then retrieved the Spartan free-flier.

The 51-G mission had originally been planned to conduct the LDEF retrieve, described in section 5.3.2.3 of this handbook.

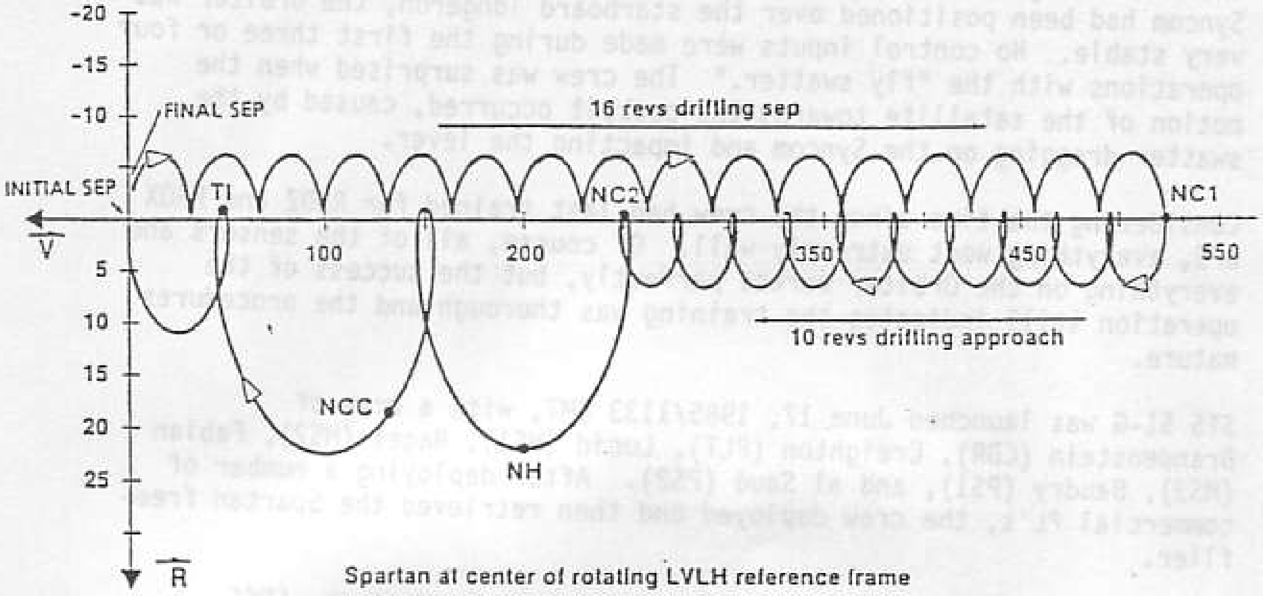
The Spartan RNDZ profile is shown in figure A-9.

Crew comments on Spartan RNDZ, STS 51-G (based on interview with J. O. Creighton about a year and a half after the mission) are as follows:

The actual flying was done by the CDR, and it was similar to the training except that visibility was much easier in the real world. The RNDZ was straightforward (the crew had originally trained for the LDEF retrieve and felt confident with the R-BAR approach), and the V-BAR approach went well.

For separation, the PL hung rock steady, "almost disappointing." During initial release, crew made maybe one or two taps on the THC, maybe even none. They backed away using about 10 +Z pulses. They planned to shoot for about 400 feet before performing the +X separation, and were concerned to be well away from the PL at that point. The RR picked it up quicker than in sims: in real life they had lock-on at 150 to 200 feet while in sims it was usually 300 to 400 feet. The RR tracked out quite a long distance and in fact never lost lock; the crew had to break lock finally.

For retrieval, the crew saw the PL visually a long, long way out. During an STRK pass at 150 kft, they could see the PL in the COAS. The burns and targeting went a lot better than in simulators. The radar, far out, would break track, and then later get solid. MDM FA3 went out.



Spartan at center of rotating LVLH reference frame

Figure A-9.- 51G Profile (Spartan)
(scale in kilofeet).

Regarding training for "no radar" case, the CDR felt it could have been done, but would have been "sporty." The difficult region is not close in, but the problem is out at 6000 to 7000 feet on the way up to the V-BAR, especially in not knowing range rate in this interval.

The crew noticed that with low Z, the closing rate increased when doing other accelerations, and these had to be broken off, or uncomfortable rates would build up.

When close, they saw that the spartan had a bad attitude. Upon getting very close in (with the PL in mid-bay just above the sill, quite a bit closer than the planned 35 feet), they used the arm to reach around to the grapple fixture, which was on top, and on the opposite side from the RMS. The crew felt that the closer the PL, the easier the flyaround.

The crewmembers all wrote individual reports within a month of the mission, but they were never assembled. CDR covered PROX OPS and MS2 covered the RNDZ. Those manuscripts are unavailable.

TABLE A-5.- STS 51-G MANEUVER SUMMARY

MANEUVER		TIG (MET)	ΔVT(FPS)	ΔVX(FPS)	ΔVY(FPS)	ΔVZ(FPS)	HA(NM)	HP(NM)
MPS DUMP	Planned	0/00:10:30	8.9	8.0	0.0	4.0	189	35
	Actual	0/00:09:52	12.9	12.5	-1.0	-3.1	192	34
OMS-2	Planned	0/00:40:36	278.7	276.9	0.0	31.5	192	190
	Actual	0/00:40:29	278.2	275.5	-0.1	38.6	192	190
MORELOS SEP	Planned	0/08:19:51	11.0	10.6	0.0	-3.0	196	192
	Actual	0/08:19:51	11.1	10.7	0.2	-3.1	196	192
ARABSET SEP	Planned	1/02:38:56	11.0	10.6	0.0	-3.0	202	192
	Actual	1/02:38:56	11.1	10.8	0.1	-2.9	202	192
TELSTAR SEP	Planned	2/00:02:36	11.0	10.6	0.0	-3.0	208	192
	Actual	2/00:02:36	11.1	10.7	0.1	-3.1	208	192
SPARTAN SEP 1	Planned	3/04:35:01	1.0	0.0	0.0	-1.0	208	192
	Actual	3/04:35:01	1.1	0.0	-0.1	-1.1	208	192
SPARTAN SEP 2	Planned	3/04:50:01	2.0	2.0	0.0	0.0	208	193
	Actual	3/04:50:01	1.9	1.9	0.0	-0.1	208	193
NC1	Planned	4/05:22:42	5.1	-5.1	0.0	-0.1	207	191
	Actual	4/05:22:42	5.3	-5.3	0.0	-0.2	207	191
NC2	Planned	4/20:41:58	2.4	-2.4	0.0	0.0	207	190
	Actual	4/20:41:58	2.6	-2.6	0.0	0.0	207	190
NCC	Planned	4/22:48:24	0.8	0.3	-0.4	-0.7	207	190
	Actual	4/22:48:24	0.9	0.5	0.1	-0.7	208	190
TI	Planned	4/23:45:48	3.7	1.7	-0.4	-3.3	207	191
	Actual	4/23:45:48	3.4	1.8	-0.3	-2.9	207	191
MC1	Actual	5/00:10:00	0.22	0.08	-0.18	0.09		
MC2	Actual	5/00:38:48	2.5	-0.23	2.35	-.76	(TIG SLIP $4^{M}24^{S}$)	
MC3	Actual	5/00:48:48	0.24	-.21	0.04	-0.10		
MC4	Not performed							
ORB ADJ	Planned	5/04:45:00	100.0	-100.0	0.0	0.0	192	150
	Actual	5/04:45:00	100.2	-100.2	0.1	-0.1	192	150
DEORBIT	Planned	7:00:34:30	279.3	-233.8	0.0	-153.0	194	0
	Actual	7:00:34:30	279.6	-234.1	-0.1	-153.0	194	0

H. STS 51-F (Spacelab 2) was launched July 29, 1985/2100 GMT, with a crew of Fullerton (CDR), Bridges (PLT), Henize (MS1), Musgrave (MS2), England (MS3), Acton (PS1), and Bartoe (PS2). Major activity involved solar observations. A subsatellite, the Plasma Diagnostic Package (PDP), was deployed for a series of precise formation flying MNVR's, and was then retrieved.

Sample PROX OPS MNVR with the PDP are shown in figure A-10.

The STS 51-F flightcrew report (December 3, 1985) described PROX OPS this way:

PROX OPS with the PDP were timelined for FD3 for a period of 9 hours and 30 minutes between MET times of 2/2 + 00 and 2/11 + 30. A summary of the preflight plan follows:

Release the PDP from the RMS, back out along the V-BAR to 300 feet; stabilize, perform a 720° Orbiter roll; restabilize; fly around the PDP three times at ranges to approximately 1500 feet maximum; cross the V-BAR in each revolution in plane to fly a wake transit; fly two additional wake transits after the third revolution; and make a standard approach and grapple.

The objective of the flyarounds was to fly through points in space which placed the Orbiter and PDP on the same magnetic field line (flux tube connection) twice during each revolution, with a desired accuracy of ±29 feet from the preflight specified point at the specified time ±1 minute. Hitting the flux tubes required an out-of-plane MNVR. After crossing the lower flux tube, a MNVR back into plane was required to perform the wake transit. The objective of the wake transit was to fly in plane from 25° below the V-BAR to 25° above the V-BAR at various ranges from 200 to 800 feet.

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The procedures developed to accomplish these objectives required a total of 27 RCS burns. The burns were targeted using the standard Orbiter software for lambert targeting via the ORBIT TGT display. Manual MNVR's were developed for the 720° roll, and the final return to the V-BAR. Based on SES/SMS development runs, the burns had to be trimmed to ≤ 0.1 ft/s to achieve the desired accuracies. Fuel margins were predicted to be tight.

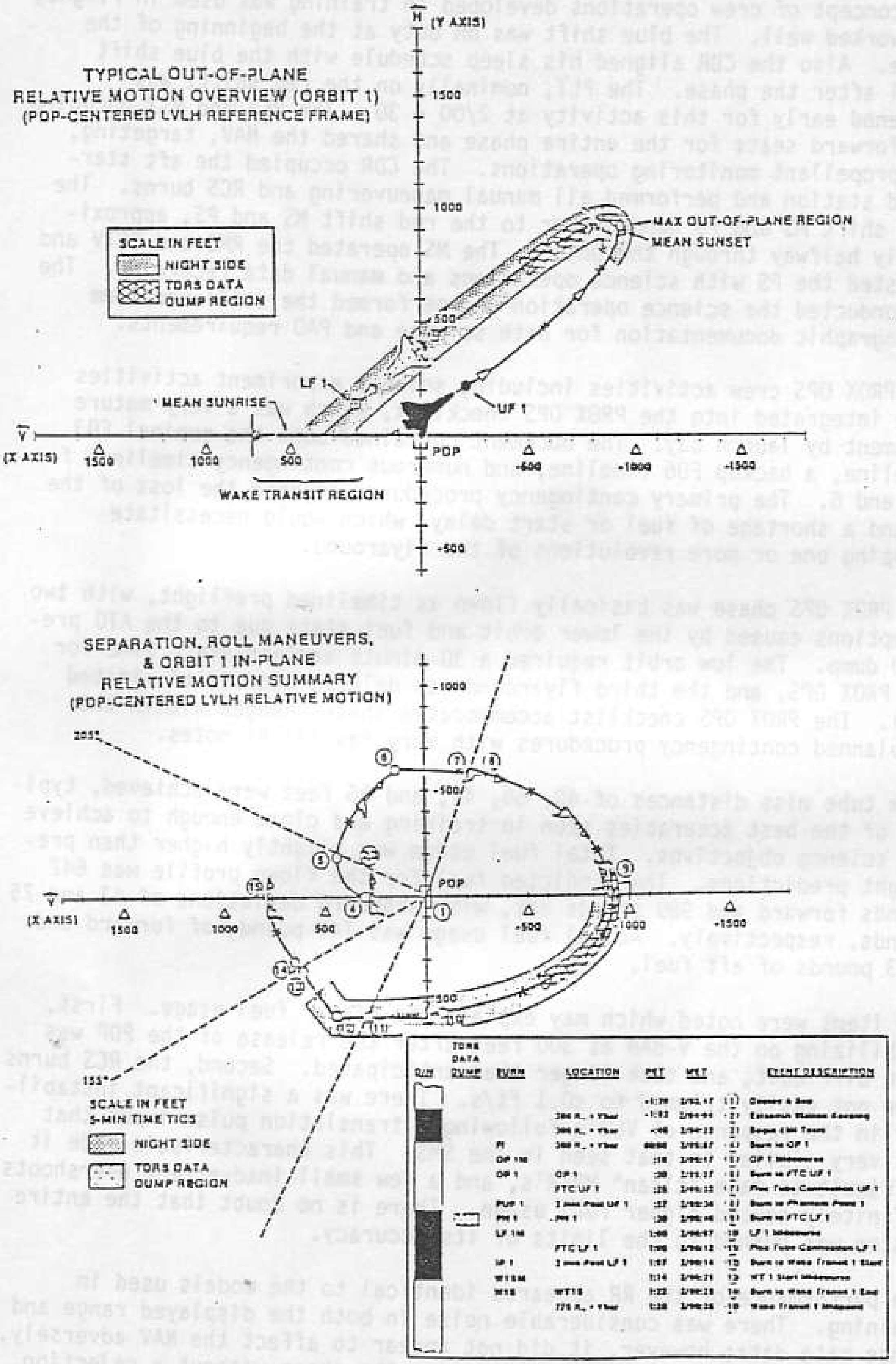


Figure A-10.- PROX OPS maneuver with PDP.

The concept of crew operations developed in training was used in flight, and worked well. The blue shift was on duty at the beginning of the phase. Also the CDR aligned his sleep schedule with the blue shift until after the phase. The PLT, nominally on the red shift, was awakened early for this activity at 2/00 + 30. The PLT and MS2 occupied the forward seats for the entire phase and shared the NAV, targeting, and propellant monitoring operations. The CDR occupied the aft starboard station and performed all manual maneuvering and RCS burns. The blue shift MS and PS handed over to the red shift MS and PS, approximately halfway through the phase. The MS operated the RMS and CCTV and assisted the PS with science operations and manual data recording. The PS conducted the science operation and performed the still and 16mm photographic documentation for both science and PAO requirements.

All PROX OPS crew activities including science experiment activities were integrated into the PROX OPS checklist, which was a very mature document by launch day. The document contained both the nominal FD3 timeline, a backup FD6 timeline, and numerous contingency timelines for FD3 and 6. The primary contingency procedures covered the loss of the RR and a shortage of fuel or start delay, which would necessitate dropping one or more revolutions of the flyaround.

The PROX OPS phase was basically flown as timelined preflight, with two exceptions caused by the lower orbit and fuel state due to the ATO pre-MECO dump. The low orbit required a 30-minute earlier start time for the PROX OPS, and the third flyaround was deleted because of limited fuel. The PROX OPS checklist accommodated these changes within the preplanned contingency procedures with very few flight notes.

Flux tube miss distances of 40, 68, 47, and 16 feet were achieved, typical of the best accuracies seen in training and close enough to achieve all science objectives. Total fuel usage was slightly higher than preflight predictions. The predicted fuel for the flown profile was 642 pounds forward and 989 pounds aft, with standard deviations of 43 and 75 pounds, respectively. Actual fuel usage was 744 pounds of forward and 1053 pounds of aft fuel.

Two items were noted which may explain the higher fuel usage. First, stabilizing on the V-BAR at 300 feet after the release of the PDP was more difficult, and took longer than anticipated. Second, the RCS burns were not easily trimmed to ≤ 0.1 ft/s. There was a significant instability in the response of VGO's following a translation pulse input that was very similar to that seen in the SMS. This characteristic made it difficult to make "clean" MNVR's, and a few small inadvertent overshoots definitely caused higher fuel usage. There is no doubt that the entire system was pushed to the limits of its accuracy.

The performance of the RR appeared identical to the models used in training. There was considerable noise in both the displayed range and range rate data; however, it did not appear to affect the NAV adversely. Over 2000 marks were incorporated during the phase without a rejection.

The PDP was stable at release except for a very slight wobble of approximately ±1°. The wobble was attributed to a slight misalignment between the spin axis of the reaction wheel and the ROT axis of the PDP. Except for this slight wobble, which was of no concern, the PDP was rock solid at grapple. The PDP was found in exactly the same attitude in which it had been released, with no observable residual roll rate. There was not the slightest effect of plume impingement noted.

Visibility of the PDP at night was satisfactory, using its running lights only. Reflectors had been added to the PDP to aid in night visibility. These were evaluated with the flashlight at close range and worked well. Neither the flashlight nor the docking light produced observable light from the reflectors at ranges of 1000 to 1500 feet. The Streamlight was not evaluated.

The long, handheld parallax rangefinder was briefly evaluated. The rangefinder indicated a range of 1100 feet when the radar indicated 1000 feet.

In summary, if the crew were to fly this phase of operations again, it would be done the same way. The importance of the highly developed, integrated checklist and the extensive, high-fidelity crew training to the success of these activities cannot be overemphasized. Success depended on zero errors, and that required extensive preflight preparation. The level of concentration required was intense, both in training and flight. The concept of using the PLT and MS2 to check each other during the hundreds of keystrokes required for targeting and navigation was considered essential to assuring the zero error performance.

* * * *

The following excerpt is from the DM5 "STS 51-F Post Flight Report" by M. Veres, March 18, 1986:

1. Procedures development for the STS 51-F PROX OPS presented several unique challenges. In addition to the usual close coordination within the JSC community, it was also necessary to coordinate with several elements of the Marshall Space Flight Center, and occasionally with the scientific investigators directly. This high level of integration was necessary because, at various times, all seven crewmembers were involved in some aspect of the PROX OPS, the basic purpose of which was to hit a series of predetermined points relative to the PDP, known as flux tubes and wake transits. A flux tube connection occurred when the Orbiter and the PDP were aligned on the same geomagnetic field line. A wake transit was induced by flying the Orbiter directly in front of the PDP at the desired range. This was accomplished by returning the Orbiter to the orbit plane of the PDP at a point 25° below the +V-BAR, and continuing to fly in plane to a point 25° above the +V-BAR. An unprecedented degree of accuracy was required to hit the flux tubes, both in terms

of position and time, while performing a series of scientific operations which were keyed to major events in the PROX OPS.

2. Two major types of techniques were developed to accomplish the science objectives. The primary technique, known as "AUTO/NAV targeting" was developed by N. Tursa and D. Dannemiller. Most of their work focused on optimizing transfer times and the placement of burns. Certain orbit targeting constants were also changed to permit short (typically 15 minute) transfer times. NAV analysis by M. D. Luneau led to changes in the NAV I-loads, which not only allowed extremely accurate NAV at unprecedented close ranges, but now has become standard for all flights.

3. The second technique, known as "manual targeting," was developed as a backup in the event of radar failure. This technique was developed by DM4/M. Veres and DM4/D. Mosel, with attitude calculations by J. Holloway and D. Edwards. The theory behind this technique is as follows:

   Since the positions of the flux tubes in relation to the PDP in the LVLH reference frame are known, it is possible to define an attitude which would point the -Z axis of the Orbiter at the PDP, if the Orbiter were at that given point. This attitude is achieved by specifying a variable body vector which, if pointed at the center of the Earth at the desired time, would result in the -Z axis of the Orbiter pointing at the PDP, provided the crew accomplishes transition inputs as required to place and maintain the PDP at the desired place in the COAS.

4. A unique FDF format was developed which conveniently and totally integrates the AUTO/NAV targeting procedures, the manual procedures, and the science operations. This was done because it was necessary to account for the possibility of the radar's failing at an arbitrary time during the PROX OPS, and because the science activities would take place concurrently with the PROX OPS. The timeline pages of the PROX OPS book contained the PROX OPS procedures in the usual two columns, but a third, central column was added to show summary level science procedure callouts for the mission and payload specialists. The facing pages contained AUTO targeting and NAV data, MNVR solution pads, and some contingency AUTO targeting data, along with the CDR's manual procedures. Manual targeting data for the PLT and MS1 were contained in tables at the end of each section and on a cue card.

5. Due to the difficulty and time involved in generating orbit targeting I-loads, and performing attitude calculations for the manual technique and the vast amount of data which would have to be uplinked, it was decided to include several detailed contingency timelines in the book. These included options for delaying the start of PROX OPS by one or two REV's, and deleting the third REV of the flyaround, both with and without performing the final wake transits. Additionally, the entire set of procedures was repeated

for use on flight day 6 (FD3 was nominal) in the event that the PROX OPS could not be performed on the nominal day. Finally, a set of "generic" contingency procedures were included that were applicable on either day.

CREW TRAINING

1. Crew training was as big a challenge as any other area of preparation for the PROX OPS. Both techniques were simple in concept, but required much practice to perform at a high level of proficiency, which was necessary to conserve fuel. Both techniques required a high level of crew coordination and checklist discipline, which was achieved during the course of the training.

2. The AUTO/NAV targeting technique utilized the standard procedures of NAV, targeting, and burn execution which have been used on several previous RNDZ flights. However, it was much more intense in that there was, nominally, a total of 27 targeted burns and several complex manual MNVR's over a period of some 8.5 hours. In many cases, there were as little as 5 to 8 minutes between burns. This left little margin for error or time for discussion in the event of unforseen problems. Also, in order to achieve the desired trajectory control, it was necessary to trim each burn to 0.1 ft/s, rather than the usual 0.2 ft/s. This was very difficult because of noise in the guidance system.

3. The manual targeting technique offered constant closed loop trajectory control, and was largely independent of radar failure or navigational errors. However, manual-targeting was a far more crew-intensive task than the AUTO technique, in that constant "out the window" attention and manual piloting corrections were required. Additionally, constant monitoring and adjustment of the attitude MNVR rate was necessary.

4. The most effective crew training from a PROX OPS standpoint occurred in the SES. This was due to the excellent quality of the visuals, the availability of correct orbit-targeting I-loads, the convenient reset points that were available about 1 year prior to launch, and the general flexibility of the facility and personnel.

5. Quite the opposite was true of the SMS. The PDP was difficult to see in the daytime at ranges greater than 400 to 500 feet (typical ranges were 600 to 1400 feet for most of the profile), and it was invisible at night or with the Earth in the background. The SMS instructors had to swap the PDP for a fake TGT and vary its brightness for day versus night passes. They generally did a good job of this, but there were times when no TGT was visible for several minutes. This was not a serious impact for the AUTO technique, but it rendered the SMS at best, useless, and at worst, counter productive for training in the manual technique.

6. Another serious SMS problem concerned the untimely delivery of proper I-loads. The crew had only one training session (an integrated sim) with the correct trajectory and I-loads, which occurred exactly 1 week prior to the scheduled launch. This is absolutely unacceptable! Since the crew had gotten used to changing nearly all of the TIG times for their targeted MNVR's because of improper SMS I-loads, negative training was actually accomplished. This assertion was proven in flight when it became necessary to change base time when we were at a lower orbital altitude because of the abort to orbit. The crew went on changing TIG's, rather than changing basetime, which slightly altered the trajectory. After much discussion within the MCC, and two or three calls to the crew, the proper procedure was finally implemented. This should never have happened, and would not have happened had the SMS been properly configured at an early date. Fortunately, the results were probably not serious.

CREW ORBITER SYSTEMS INTERFACE

a. CCTV Operations

The crew reported that the CCTV ranging charts worked well; however, the pan and tilt adjustments were easily misaligned after PRCS firings by as much as 5° to 10°. It is therefore recommended that the cameras be realigned just prior to starting the final approach to grapple.

The crew noted that the PDP, as seen in the CCTV, was a "blob that changed its shape." This problem was especially bad at night. When the Sun was in front of the PDP (from sunrise to noon), an image good enough to use the ranging rulers could be obtained, but only after much dedicated effort. The poor image made it difficult to detect small rates, which means that while the PROX OPS could still have been accomplished using the manual technique, it would have cost more fuel. This problem also contributed to the difficulty in establishing the precise stationkeeping position required to set up for the manual roll MNVR. The CDR commented that he finally resorted to using the radar angles for this task. The CDR also noted that while the CCTV image jumped during PRCS firings, the motion quickly damped out.

b. RR Operations and Alternate Ranging Devices

The range rate data provided by the radar was not quite as noisy as that in the SES radar model. However, it was so noisy that the CDR found it necessary to use either the navigated state or apply a "mental filter" to judge his range rate.

The inertial LOS rate needles were "a little jumpy," but still usable, if time was taken to watch them and apply a mental filter. Fine control was not possible, but they may be useful at long ranges. Other RNDZ crews have made similar comments. Their usefulness may be a function of range and TGT size, radar reflectivity characteristics, and attitude rates. Consideration should be given to developing a procedure to use this information when possible.

MS2 made several attempts to determine range using the parallax rangefinder. The MS2's attempts resulted in a bias of about 10 percent long over ranges of 600 to 900 feet, as compared to the radar.

c. Beta Angle

The PROX OPS was performed while the beta angle was in the vicinity of +20°. Due to the sequence of events, this was a factor only during the initial stationkeeping and during the descent to the V-BAR following the last wake transit end (WTE) MNVR. Both of these tasks were performed manually. The CDR felt that although there were times when he had to shield his eyes from the Sun, a 20° beta angle was not a problem, and a "somewhat smaller" angle would have been acceptable.

In the event of a smaller beta angle, the CDR was confident that he could have "flown on instruments," provided that the radar was working. In fact, that method was used to establish the initial V-BAR stationkeeping. This method seems to be the best in situations where precise control of positions and/or rates is required.

d. Orbit Targeting

Although a detailed analysis of targeting and guidance performance is beyond the scope of this report, a few general remarks are in order.

- All onboard burn solutions were well within precomputed limits.
- As expected, it was very difficult to trim the burns to within 0.1 ft/s. This was especially true with MNVR's having short (5 min) transfer times. There appears to be a tradeoff between using short transfer times (which minimizes the propagation of trim errors) and the more accurate trimming possible with longer transfer times. In the latter case, the original trim error to be propagated would be smaller. It may also be possible to alter the VGO corrector task in Lambert guidance such that it would result in less noise in the VGO's presented to the crew.

The large trajectory dispersion following the W3S burn is as yet unexplained, since the crew successfully performed that burn, and the residuals were small. An option to be explored is whether it would have been better to perform the wake transit start and end burns based on elevation angle, rather than time.

e. Flight Data File (FDF)

The crew commented that while informal communication and advice were valuable, the FDF should incorporate as much information of this nature as possible. In other words, "the FDF is the last word," and all last-minute changes should be included.

The only serious deficiency of the PROX OPS book in this regard, of which I am aware, concerns the post-phantom-point midcourse maneuver. It was discovered that trajectory dispersions due to trim errors performing a midcourse about 10 minutes after the PH burn, improved the lower flux tube accuracy. Discussions with the crew and flight director resulted in the decision that the post-PH midcourse would be executed per a real-time call based on an evaluation of PH burn residuals. Although all interested parties understood this agreement, and it worked smoothly in real time, a procedure for performing the targeting and execution of the midcourse should have been included in the PROX OPS book, preceded by an "if required" statement, much like what was done with the second TDRS data dump. However, it should be noted that a teleprinter message was transmitted which contained TIG times and TGT set numbers for the midcourses. Also, the crew commented that they were pleased with the book, and that "if we had to do it again, we wouldn't change a thing."

The CDR commented that it would have been handy to have translation pulse sizes, and perhaps attitude DB data on the "Execute RCS Burn" cue card. This probably comes under the heading of a "crew preference item," but the format would be useful, particularly for missions of this nature. This option should be made available for each crew.

SUMMARY

In summary, several key points merit emphasis.

1. The flux tube connections and wake transits were accomplished with sufficient accuracy to obtain good scientific data.
2. The amount of propellant used was acceptable.
3. A postflight examination of the crew's PROX OPS books used in flight revealed meticulous attention to detail, exemplary checklist discipline, and good crew coordination. These factors were chief contributors to a successful mission.
4. Procedures development was a long, arduous process, spanning some 2 years. Many avenues were explored during the early phases, resulting not only in good procedures and a successful flight, but in a greater understanding of the capabilities of the current system, and new ideas concerning how it might be improved. Some of those ideas have already been incorporated. One of the prepublished

contingency procedures (the REV 3 waveoff) was a key to mission success following the abort to orbit.

5. It is clear that the SES is the best place to conduct training for RNDZ and PROX OPS missions; and that DM4 personnel should support all related phases of the crew's training.

6. No adequate backup for the radar has yet been found. All alternate ranging devices tested to date have been found to have limitations in useful range, accuracy, or both. The Ku-system has had problems in flight. We are fortunate that radar failures have not occurred during a RNDZ or PROX OPS mission.

I. STS 51-I was launched Aug 27, 1985/1058 GMT, with a crew of Engle (CDR), Covey (PLT), Van Hoften (MS1), Lounge (MS2), and Fisher, W. (MS3). After deploying a commercial payload, the crew performed a RNDZ with the Syncom, which had broken on STS 51-D, and repaired it.

The rendezvous profile is shown in figure A-11. Specific features unique to this mission include elliptical orbit, stable relative position post-NSR, and preplanned in-close flyaround.

The "Rendezvous FDO" (Brian Jones) produced the following account of mission maneuvers:

- Three deployables, one RNDZ. Syncom was in an elliptical orbit (160 by 235).
- Orbiter was inserted into a 190 n. mi. circular orbit for the deploys. Phasing (variable orbit) was not allowed until all three deployables were out of the bay. This was a premission constraint imposed because of the late manifest change. Both PAM's required at least a 190 n. mi. circular orbit because they were using the heavy, beefed-up nozzles and without them, their insurance rates would go up a great deal.

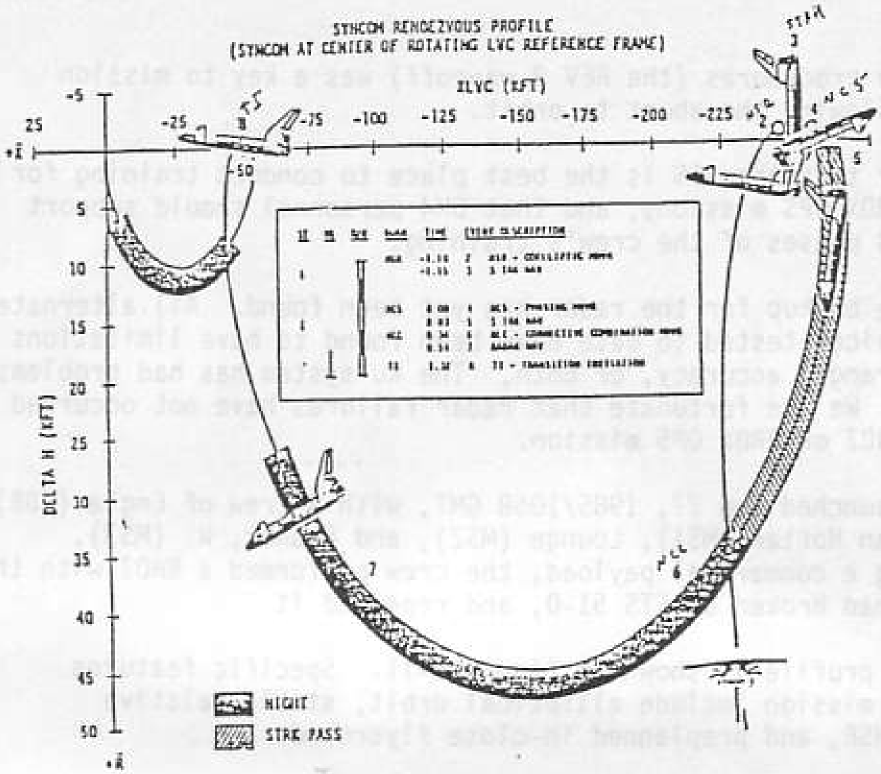


Figure A-11.- Rendezvous profile, STS 51-I.

- NC1 TIG selected to fix the line of apsides.
- NC2, NC3, NC4, and NH2 were planned for 0 ft/s (i.e., no posigrade bias) to yield to maximum launch window. This also allowed them to be deleted in real time without any effect on the profile.
- NSR was placed as late in the profile as possible (between NH and NC5) to yield the maximum launch window. NSR was required to set terminal phase lighting.
- Because of the NSR placement, this was a one-ST pass RNDZ. The profile is more sensitive to dispersions at Ti as a result.
- Typical one REV transfer to Ti because of the EVA requirement (crew workday).
- The following postflight report was prepared by the Rendezvous Procedures office (DM43).

TABLE A-6.- 51-I NAVIGATION PERFORMANCE

Event	Star TRK 0	Star TRK 1	RR Pre-TI	RR Post-TI
Lock on range	303,802 ft (50 n. mi.)	333,072 ft (54.8 n. mi.)	146,935 ft (24.2 n. mi.)	54,500 ft (9.0 n. mi.)
Lose lock range	304,429 ft (50.1 n. mi.)	LOS	48,000 ft (7.9 n. mi.)	-85 ft
1st SV update	186 ft	814 ft	103 ft	58 ft
Last SV update	13 ft	530 ft	0 ft	LOS
Range marks	N/A	N/A	163	772
R-DOT marks	N/A	N/A	162	772
Angles marks	23	158	161	697
Time	~3 min	~19 min	~22 min	~138 min

The first STRK pass, though short, was very good. The first SV update was 186 feet, indicating that the ground tracking was good. The last update was 13 feet which indicated that the SV was well on the way to being converged. Even though only 23 marks were processed, the results were excellent. A good first STRK pass is protection against subsequent STRK failure.

The second STRK pass was also a good pass. The first SV update was 814 feet while the last update was 530 feet, occurring after 158 marks. This pass lasted approximately 19 minutes and provided the majority of the STRK NAV with the best viewing geometry for this flight.

The radar first detected the Syncom at 27.8 n. mi. This was a momentary detection with full radar lock-on not occurring until 24.2 n. mi. The last radar marks used for Ti targeting were taken into NAV 7.9 n. mi. The first SV update was 103 ft and the last update, prior to going to OPS 202, was a 0-foot update. Since the Ti burn was a left OMS burn, the radar did not drop lock during the maneuver to burn attitude during the burn, nor during the return to -Z axis TGT track. However, when OPS 202 is entered prior to Ti, the input from the radar is no longer processed by the NAV software. Range and range rate mark processing resumed as soon as the crew returned to OPS 201. The post-Ti lock-on range represents the point at which the radar angle marks were re-enabled and full NAV processing resumed.

The dispersions at Ti were 1458 feet long and 365 feet high from the targeted position. This resulted in an MC2 TIG slip of 1 min 23. The out-of-plane null for this flight was 0.13 ft/s.

TABLE A-7.- 51-I PROPELLANT USAGE

Propellant Usage (LB)

Eveny	Forward	Aft	I/C	OMS	Total
NSR burn	26	9	30	1008	1073
NC5 burn	26	0	49	464	539
Ti burn	22	0	25	493	540
MC 1	-	-	-	N/A	25
OOPN	-	-	-	N/A	28
MC 2	7	0	12	N/A	19
MC 3	4	0	18	N/A	22
MC 4	9	0	14	N/A	23
Manual phase	84	0	183	N/A	267
V-BAR approach to low Z	26	0	0	N/A	26
Low Z to sunset	70	0	130	N/A	200
Sunset to no low Z (night)	124	0	76	N/A	200
Total V-BAR app. to no low Z	220	0	206	N/A	426
SK to sunrise (31 min)	0	0	83	N/A	83 (2.68 lb/min)
Period of rate matching	397	0	436	N/A	833

The propellant usage during the RNDZ portion of the flight (beginning of the RNDZ book to the V-BAR arrival at the end of the manual phase) was within predictions. The NSR burn was a large burn (total ΔV 48 ft/s) while the NC5 and Ti burns were both less than half that size. All the midcourse burns were of the same magnitude and roughly equal in prop cost. Manual phase (2 minutes post-MC4 to stable on the V-BAR) cost a total of 267 lb which was only 38 lb above the predicted mean and well within 1 sigma.

During the V-BAR approach, the prop usage was nominal. However, when the flight entered the PROX OPS phase, the propellant usage deviated tremendously above the predicted. When it came time to leave low Z mode, the crew punched the low Z pbi, but because of sunshafting coming in through the overhead windows, they could not read whether the pbi light was on or off -- off being the no-low Z mode indication (i.e., NORM Z). Since they were not sure that they had left low Z mode, they pressed the low Z pbi again. During this time, they were LOS and the MCC could not offer any insight. Postflight data shows that the initial depression of the low Z pbi did take the Orbiter out of low Z mode and that the second depression returned the vehicle to low Z mode. The crew, believing incorrectly that they were now in NORM Z, subsequently performed the final braking and establishment of 35-foot stationkeeping in low Z mode as opposed to norm Z mode as called for by the procedures. This cost 400 lb of propellant rather than the expected 40 to 50 lb.

After stabilization at the 35-foot stationkeeping position, the crew recognized that the low Z mode was still enabled and disabled it. At this point, all attention was focused on the two EVA crewmembers as they struggled to get the capture and grapple bars out of their carrier. The Syncom was tucked lower than 35 feet in the bay for better lighting at night, and it was slowly drifting aft. When the crew realized that the Syncom was too far aft, near the tail, the view of the TGT out the aft windows (vice the former view out the overhead windows) caused temporary confusion between aft sense of -Z (normally, facing "up") and -X (normally, facing "aft"), and improper THC inputs were executed ("sense" had always been "-Z", but several THC inputs were made as if "sense" were "-X"). The TGT was already over the OMS pod and it was inadvertently plumed. This induced unplanned rates on the Syncom which turned out to be difficult to match. In an attempt to match Syncom rates with Orbiter rates, the crew began a period of approximately 30 minutes where postflight data shows Orbiter rates greater than 0.2 deg/s and at times exceeding 0.8 to 1.0 deg/s. The propellant usage during this period of attempted rate matching totaled 833 lb. Completely matching the Syncom rates turned out to be unsuccessful. Astronaut James Van Hoften finally acted as a "flexible end effector" and wrestled the last remaining rates out of Syncom.

LESSONS LEARNED

The lessons learned from the flight have impacts on flight design, procedures, and training. The flight design considerations involve the planning for STRK passes. Upon examination of dispersion data, we found that the lack of the first STRK pass leads to greater dispersions at Ti with subsequent dispersions at V-BAR arrival. If the radar is working for the terminal phase, this represents no problem. However, there could be major impacts to a radar-failed terminal phase. The three sigma dispersion cases could require more propellant than is currently budgeted and put mission success into jeopardy. The flight designers need to provide as much time as possible for the first STRK pass with the goal of providing two full STRK passes prior to Ti. Procedurally and during flight, every opportunity must be given the crew to maximize the STST data during the STRK passes.

A lesson learned from the integrated sims involves the NAV management immediately post-Ti. Post-Ti we nominally go back to use the RR. If

TABLE A-8.- 51-I MNVR SUMMARY

MNVR	TIG	ΔV	VX	VY	VZ	Ha	Hp
MPS DUMP	0/00:09:35	10.0	9.6	0	-2.7	191	-
OMS-Z	0/00:40:21	278.6	276.4	15.7	31.2	191	190
AUSSAT SEP	0/06:50:14	11.2	10.7	0.1	-3.2	196	190
ASC SEP	0/11:24:32	11.1	10.6	0.1	-3.2	202	190
SYNCOM F4 SEP	2/00:05:54	15.2	14.6	-0.1	-4.3	211	190
NC1	2/06:12:42	2.7	2.7	-0.1	-0.1	212	191
NH1	2/06:58:28	35.7	-35.7	0.1	-0.8	212	170
NPC	3/05:34:21	8.8	0.1	8.8	0.2	212	170
NC2	3/06:39:07	0.9	-0.9	0.1	0.1	212	170
NSR	3/20:24:15	47.7	47.7	-0.1	-0.9	239	170
NC5	3/21:38:56	17.7	-17.7	0.1	0.3	233	166
NCC	3/22:12:55	1.3	-0.7	0.0	1.1	233	166
TI	3/23:10:55	13.5	13.5	0.6	1.4	238	169
MC1	3/23:33:37	0.6	-0.1	0	0.6	238	169
PLANE NULL	3/23:46:44	0.2	0.0	0.2	0.0	238	169
MC2	4/00:01:30	0.4	-0.3	0.0	0.3	238	169
MC3	4/00:11:30	0.4	-0.3	0.0	0.3	238	169
MC4	4/00:21:30	0.3	0.2	0.1	-0.2	238	169
VBAR	4/00:49:15	-	-	-	-	239	170
SYNCOM F3 SEP1	5/04:30:30	2.1	0.0	2.1	0.0	239	170
SYNCOM F3 SEP2	5/04:45:30	3.1	3.0	0.0	0.1	241	170
ORBIT ADJUST	5/22:20:00	15.2	15.2	-0.2	0.0	242	178
DEORBIT	7/01:13:00	475.6	-364.5	0.0	-305.3	184	-

the radar has a problem and it is not giving valid NAV data, crews need to go immediately to the STRK and take STRK angles. Once this angle data is assured, then they can return and attempt to troubleshoot the radar. During the sims, we spent too much time trying to troubleshoot the radar prior to going to the STRK. The result was a shortened STRK pass which yields poorer NAV data.

The crew also had problems during the off-nominal PROX OPS after the Syncom was plumed. Part of this problem was discovered during a crew debriefing. Since the Syncom was held lower than 35 feet (approximately 25 feet), the CDR could see the satellite out the aft window. He mentally changed his reference frame for the THC from -Z to -X. The Orbiter sense switch, however, was not physically changed. This exacerbated the aft movement of the Syncom and contributed to its being plumed. While trying to match rates, the crew also put the Orbiter into pulse mode in pitch and yaw. This was not called for in the nominal procedures and was not examined as a contingency. This configuration is propellant inefficient.

J. STS 61-B was launched November 27, 1985/0029 GMT, with a crew of Shaw (CDR), O'Connor (PLT), Ross (MS1), Cleave (MS2), Spring (MS3), Walker, C. (PS1), and Neri (PS2). Several commercial PL's were deployed and two EVA's were performed for space construction tests. A TGT was manually deployed for new PROX OPS techniques testing involving the OEX DAP.

The purpose of this flight test was to expand the knowledge gained from OEX DAP tests performed on STS 51-G. The OEX DAP was developed by the Charles Stark Draper Laboratory with potential application to the present Orbiter or future space vehicles. The most rigorous test associated with the STS 61-B activity was known as "real target stationkeeping," for the purpose of evaluating the interaction of the closed loop RR and navigation system with the DAP. The target, consisting of two 15-inch diameter aluminum disks interlocked together to form a "sphere-like" object, was deployed by an EVA crewman following completion of a scheduled EVA. It was equipped with highly reflective tape which allowed nighttime visibility out to a maximum of 500 feet with the Orbiter overhead light, as determined by tests at Ellington Field.

The final version of the test plan (as documented in the STS 61-B PROX OPS book) called for a brief period of 35-foot stationkeeping to qualitatively evaluate the DAP manual handling qualities. An initial separation to 300 feet on the +V-BAR was performed, where, after manually establishing stationkeeping, the DAP was to be placed in the "position pulse" (POS PLS) mode to automatically stationkeep within a predefined position sphere, using the low Z mode. After 30 min, low Z was to be exited, and the POS PLS mode used to command an automatic translation to 400 feet on the +V-BAR, where another 30 min of SK was to be performed, this time in NORM Z. The Orbiter next was to automatically translate 100 feet below this point on the +V-BAR for a final 30 min of NORM Z SK, followed by a posigrade final sep MNVR and deactivation of the OEX DAP.

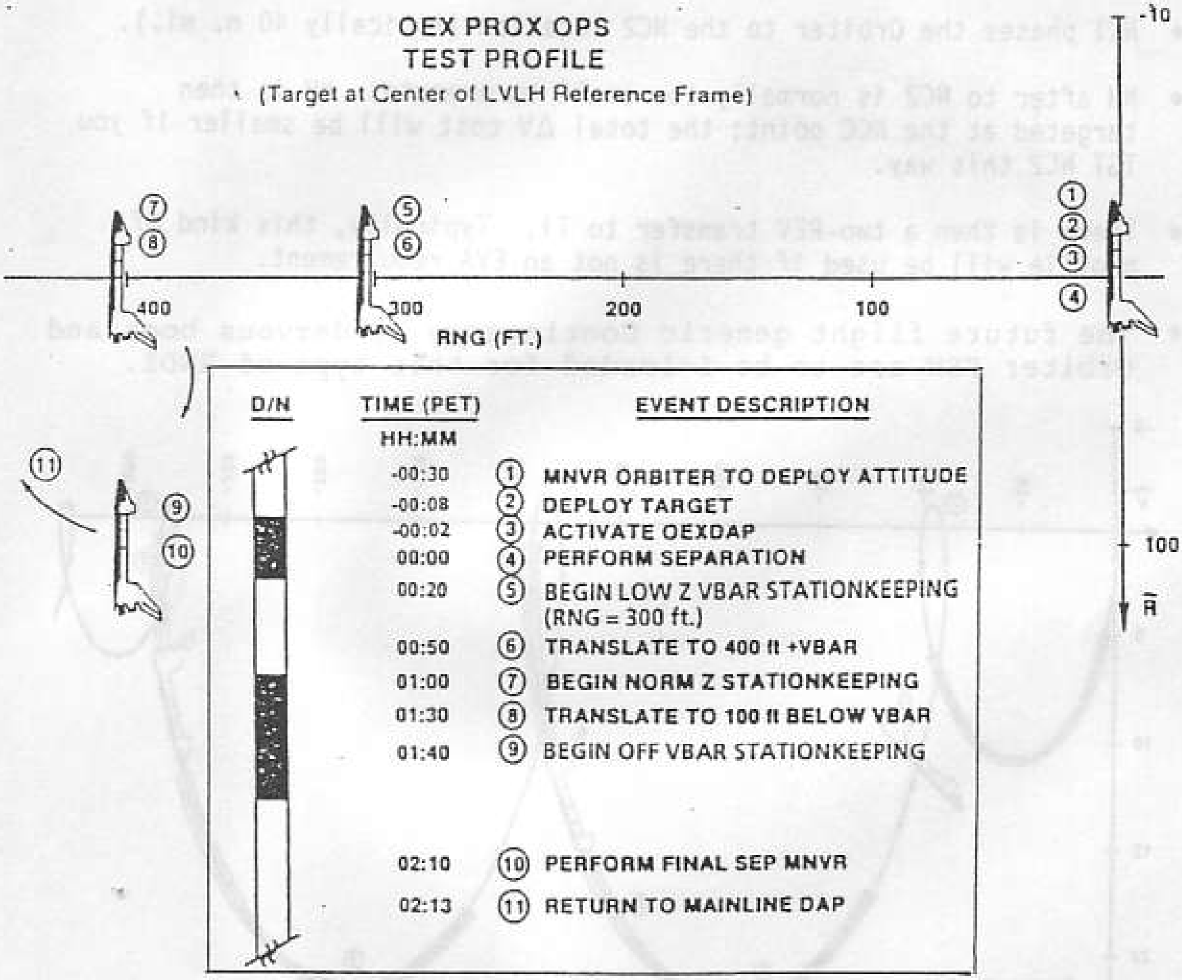
Unfortunately, a last-minute decision was made to leave the Ku-band system off the vehicle, due to KSC Orbiter processing flow schedule constraints. Therefore, only limited flight test data was obtained about the OEX DAP manual handling qualities. The crew performed 10 minutes of SK with the conventional DAP, then activated the OEX DAP. Of the approximately 1 hour of OEX SK, about 15 min were spent in "quiescent stationkeeping", with propellant usage comparable with preflight predictions. The remaining 45 min was used to perform a "tracking task," consisting of a series of small manual translation maneuvers to evaluate the OEX DAP manual handling characteristics. Qualitatively, the OEX DAP manual handling characteristics were found to be generally satisfactory.

Because of the in-flight absence of the Ku-band system, the preflight procedures development/validation work done in the SMS (coupled with the comprison runs done in the SES) may well constitute the most thorough and meaningful evaluation of the automatic PROX OPS features of the OEX DAP. One of the most important results of that process is that while the difference in propellant usage between the two DAP's was statistically indistinguishable (perhaps partially due to the small number of runs available), the OEX DAP did not demonstrate a capability to duplicate the precision which a human pilot can achieve in flying the PROX OPS. This is not necessarily bad, since there may be future requirements to remain close to another vehicle for long periods of time, but precise SK is not necessary to perform that task.

The limited amount of procedures development time did not allow sufficient experimentation in varying OEX DAP setup values. The SMS was the only JSC facility with the OEX DAP software, and only 16 hours of useful, dedicated procedures development time wasere obtained. If more procedures development time had been available in the SMS, experimentation might possibly have resulted in greater precision with acceptable propellant usage.

Another fringe benefit of these studies was the development of the capability to perform off-V-BAR SK. In this case, SK was performed 100 feet below a point 400 feet along the +V-BAR. Although not tested on orbit, this activity was satisfactorily accomplished in the SES, with fuel usage comparable to more conventional SK locations. However, it was a more crew-intensive task, because off-V-BAR locations are inherently unstable. Therefore, one would not expect to perform this type of activity for extended periods of time. SES work was done at ranges of 300 feet and 400 feet on the +V-BAR, both 100 feet above and 100 feet below. A position below the V-BAR is preferred because visual cues with the COAS are better, and the propellant usage is almost exclusively from the aft system.

In conclusion, the OEX DAP was shown to have many features which would be highly desirable to have on the Orbiter. Some of them may be mandatory for unmanned vehicles which will operate in an autonomous mode. Unfortunately, there was not enough time between the final decision authorizing the "real target stationkeeping" tests on STS 61-B and the launch to develop a rigorous test plan in an optimum manner and to smoothly integrate it into the overall mission planning process. The loss of the Ku-band system just 3 weeks prior to launch made it impossible to accomplish any of the major preplanned PROX OPS test objectives; the whole operation was on such a "success-oriented" schedule that it was not possible to develop a worthwhile "no-radar" test plan while struggling to develop the nominal test plan. Therefore, further testing is required before any of these capabilities can be implemented.

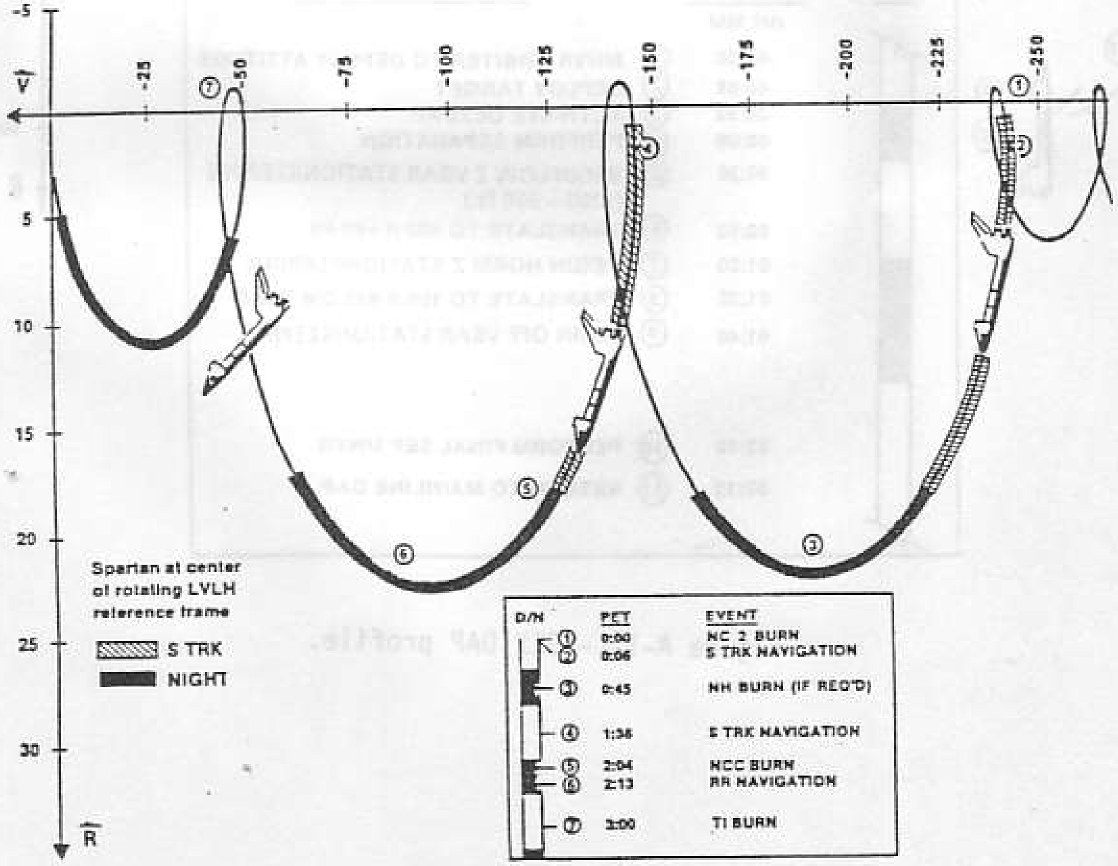


D/N	TIME (PET) HH:MM	EVENT DESCRIPTION
	-00:30	① MNVR ORBITER TO DEPLOY ATTITUDE
	-00:08	② DEPLOY TARGET
	-00:02	③ ACTIVATE OEXDAP
	00:00	④ PERFORM SEPARATION
	00:20	⑤ BEGIN LOW Z VBAR STATIONKEEPING (RNG = 300 ft.)
	00:50	⑥ TRANSLATE TO 400 ft +VBAR
	01:00	⑦ BEGIN NORM Z STATIONKEEPING
	01:30	⑧ TRANSLATE TO 100 ft BELOW VBAR
	01:40	⑨ BEGIN OFF VBAR STATIONKEEPING
	02:10	⑩ PERFORM FINAL SEP MNVR
	02:13	⑪ RETURN TO MAINLINE DAP

Figure A-12.- OEX DAP profile.

K. STS 51-L was lost during launch phase on January 28, 1986, along with the crew of Scobee (CDR), Smith (PLT), Onizuka (MS1), Resnik (MS2), McNair (MS3), Jarvis (PS1), and McAuliffe (teacher-in-space). One mission objective was to have been deployment and retrieval of the Spartan-Halley free-flier. The planned rendezvous profile is shown in figure A-13.

- This was a typical deploy and retrieve RNDZ.
- The separation MNVR is a canned MNVR executed on lighting. This eliminates the need for an NSR to fix the lighting or a propellant penalty to fix the lighting.
- NC1 phases the Orbiter to the NC2 location (typically 40 n. mi.).
- NH after to NC2 is normally too small to execute. NH is then targeted at the NCC point; the total ΔV cost will be smaller if you TGT NC2 this way.
- There is then a two-REV transfer to Ti. Typically, this kind of profile will be used if there is not an EVA requirement.
- The future flight generic Contingency Rendezvous book and Orbiter FSW are to be I-loaded for this type of RNDZ.



D/N	PET	EVENT
①	0:00	NC 2 BURN
②	0:06	S TRK NAVIGATION
③	0:45	NH BURN (IF REQ'D)
④	1:36	S TRK NAVIGATION
⑤	2:04	NCC BURN
⑥	2:13	RR NAVIGATION
⑦	3:00	TI BURN

Figure A-13.- Rendezvous profile, STS 51-L.

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