STS Rendezvous Evolution

1: The Peculiarities of STS Rendezvous Operations

Initial STS rendezvous design assessments (mid-1970's) called for continued use of the co-elliptic scheme which had been so effective for Apollo. As John Young, veteran orbital rendezvouser and STS-1 mission commander, put it in his typical succinct style, "What's wrong with the way we BEEN doing it?" As it turned out, there were a number of new factors to be considered.

From the outset, Gemini and Apollo design had been optimized for rendezvous, from the basic structures of the chaser/target vehicles to the entire flight profile from liftoff through linkup. Targets were cooperative, with transponders and lights. Docking mechanisms were validated by physical mating pre-flight. The targets were usually maneuverable, so they could line up their orbits for the convenience of the chaser vehicle. And they were steady, both massive and with active attitude control systems.

But STS rendezvous would be different in every respect. The rendezvous would be only part of a complex mission with other trajectory constraints (especially for deploying fee-paying payloads). Actual mating hardware would never be tested together, so interface equipment on the STS side would have to be designed based only on target vehicle documentation. The targets would usually be non-cooperative, with no transponders or lights, and they would usually be passive, with no maneuvering capability (they might not even have the ability to go to a convenient attitude). These less-than-optimized conditions suggested the need for a far more cautious approach trajectory to the target, with easy stopping points at which to pause and consider unexpected situations/configurations.

The "classic" Gemini/Apollo rendezvous missions had involved "ground-up" profiles in which the chaser was launched in pursuit of an already-orbiting target, but the STS was supposed to also be able to carry out several radically new types of rendezvous missions. One was the deploy/retrieve scenario (e.g., Spartan) which involved several days of drifting separation followed by a rendezvous from a starting point trailing on the target's velocity vector (the "VBAR"). Another mission involved a high deploy of a payload followed by a drop to a lower orbit for pickup of another payload (early scenarios envisaged an LDEF deploy plus Solar Max servicing on one flight, and an Hubble Space Telescope deploy plus LDEF retrieve on a later flight). These profiles did not begin with the "classic" starting point of the chaser far behind and below the target.

The physical structure of the shuttle orbiter also promised to be a problem. Apollo flew its rendezvous maneuvers with its target line-of-sight forward along the X axis (the crew looked forward from their seats), and it performed small translation burns with RCS jets mounted in four "quads" equi-spaced around the waist of the service module (big rendezvous burns needed the OMS); also, there was no OMS/RCS interconnect capability on Apollo. But shuttle would fly a rendezvous with its -Z axis boresighted on the target (the crew stood at the aft control station looking out the overhead window), and its small translation burns would come from an RCS system split between a small isolated forward tank and a set of aft tanks with interconnect capability to the OMS tanks. With the Orbiter's center of mass closer to the aft jets, the ratio of propellant used would be about 2:1 aft:forward, BUT the aft tanks could draw upon the much greater reserves of the OMS system. This meant that large translations along the line-of-sight would cost dearly in terms of the limited forward RCS supplies, which would impose a severe constraint on total maneuver capability.

Communications coverage would be another difference. The STS was expected to use the TDRSS to maintain nearly continuous contact with the Mission Control Center (MCC). Previous Apollo requirements for onboard fully autonomous operations beyond reach of the MCC (either on the back side of the Moon, or just out of range in low earth orbit) could be relaxed.

Also, the Orbiter's Remote Manipulator System (RMS) was completely new. Gemini/Apollo achieved final linkup by approaching along the docking axis at a non-zero velocity and performing a "controlled collision". But the STS would have to move right up next to the target and then completely null all relative rates, both in translation and rotation, before the robot arm could grapple the target.

The Gemini and Apollo vehicles generally were small (or at least equal) in size relative to their targets, so that in the 1960's the effects of their RCS plumes had not been a serious concern. But the Orbiter was much bigger than its targets, so RCS plumes threatened major impact on many of the small targets under consideration (some were only a few percent of the mass of the orbiter). A shuttle orbiter flying an Apollo-type approach with classical high closing rates (30-40 ft/sec within several thousand feet of the target) and consequent forceful braking burns could lead to all sorts of unwanted effects, ranging from contamination to tumbling to separation.

These "plume effects" promised to make the terminal phase of the STS rendezvous profile strikingly different. In the mid-1970's, careful analysis of Orbiter/target proximity operations soon established the extreme sensitivity of this mission phase, which had in past programs been merely an uninteresting tail end of rendezvous. One result of this early work was the realization by NASA analysts (from the Mission Planning and Analysis Division, or MPAD) that a combination of forward and aft RCS jets could be fired to create braking force along the Z axis. This fortuitous unintentional result of the RCS thruster architecture was quickly implemented into the STS autopilot design as "LOW Z" mode.

In preparation for shuttle operations, RCS jet plume models were developed to a much more sophisticated and hi-fidelity level than ever before, and analysis/simulation work confirmed the delicacy of proximity operations. This was particularly true for potential payloads lacking active attitude control systems, which had to rely entirely on gravity gradient forces for orientation control.

To provide sufficient finesse for this close-in maneuvering, a special Orbiter flight software specialist function named "PROX OPS" (for "proximity operations") was designed. It used Clohessy-Wiltshire relative motion equations to compute maneuvers when within several miles of the target. This spec function complemented another spec function for long-range operations, which contained a package of software (the Orbital Maneuver Processor, or OMP) capable of targeting any on-orbit rendezvous burn (including 2-impulse maneuvers, coelliptic maneuvers, and multi-rev targeting). However, a subsequent onboard software "scrub" forced the deletion of much of the OMP targeting. The Prox Ops logic was expanded to include Lambert targeting, and the result was called the Orbit Targeting (ORB TGT) specialist function. The crew would use these specialist functions to carry out rendezvous navigation and targeting in flight.

So STS rendezvous promised to be a "back to basics" re-invention of the entire rendezvous profile based on a wide range of changed conditions. However, a leisurely development of a new profile "from scratch" was not to be possible, because in 1977-8 an early, urgent rendezvous flight assessment was dropped onto the designers: Save Skylab!

2: The Skylab Re-Boost

By the second half of the 1970's, with Apollo relegated to the history books, the challenge of space shuttle orbital rendezvous sharpened. The flight assessment "race" was on to get a shuttle mission off in time to forestall the orbital decay of Skylab (expected to occur in 1980-1), so that a rendezvous could be performed in time to attach a booster stage and save the space station. A special astronaut crew (Fred Haise and Jack Lousma) was assigned, and plans called for them to take the fifth (later, the third or even the second) shuttle on the mission sometime in 1979-80.

The Skylab was in a low (about 150 nm and dropping), elliptical orbit, which presented dynamic complications. There were also problems with onboard navigation compatibility. The baseline Skylab-style sequence did not sufficiently control the lighting or the range prior to final approach, and it could have a significant ΔV penalty for elliptical target orbit rendezvous. An early STS document had "baselined" a double co-elliptic rendezvous profile for STS operations (with a height difference, or "ΔH", first of 20 miles, then later 10 miles), but analysis revealed problems with it.

The early STS mission assigned to the Skylab rendezvous also presented special limitations. No radar could be assumed. Limited (if any) onboard targeting would be available. There would be reduced capability in autopilot and attitude control software. There would be no RMS.

The five-day baseline mission would be allowed up to four days to make the rendezvous phasing. Launch windows called for an on-time launch with no yaw steering. The initial orbit would be about 100 nm high. Ground navigation and MCC targeting would be used to insert the Orbiter into an orbit that would phase toward Skylab from behind and below. Later, at a range of about 300 nm, the Orbiter entered a coelliptic orbit 20 nm below the Skylab.

Beginning at orbital noon, the Orbiter used star tracker sightings to improve relative navigation. Onboard navigation now became prime, while the MCC would use the Orbiter's data and an old Apollo "OMP-like" program to compute a Lambert maneuver to raise the orbit to be coelliptic just 10 nm below the Skylab. This altitude adjust maneuver used a 37 minute transfer, followed by another circularization maneuver. A closing rate of about 100 ft/sec was established.

Beginning at the next orbital noon, the Orbiter took more star tracker sightings and again updated its relative navigation. The TPI (Terminal Phase Initiate) maneuver was scheduled at an elevation of 27 degrees, with a transfer time of 130 degrees, as in Apollo.

Unfortunately, TPI occurred after sunset, which eliminated the former ability to perform it manually as a backup to onboard attitude control and targeting capabilities. This was necessary because flight designers wanted to use the full pre-TPI pass for star tracker navigation, and also because the manual terminal phase had to begin after sunrise (Gemini and Apollo were able to do that phase in darkness by using target-mounted lights).

Two midcourse correction burns were scheduled after TPI, at intervals of 10 minutes. Manual braking followed as the Orbiter held inertial attitude after the second correction burn. Initial plans were for the Orbiter to continue straight into the Skylab, where the closing rate of 40 ft/sec was braked by RCS firings, with grappling operations occurring near noon. When it later became clear that no grappling hardware would be ready in time for the Skylab rescue mission, the plan was modified: the Orbiter was merely to park on the +VBAR (leading the target in its orbit) to deploy the teleoperator vehicle for remote-controlled flyover and docking. Then it would transfer to a stationkeeping point on the -VBAR (trailing the target in its orbit) for boost ignition.

A number of fascinating devices had been considered for the actual boost. One early plan involved an Inertial Upper Stage, attached by RMS. Another called for a tow cable arrangement during an OMS firing. The final plan was a 12,000 lb. "space tug".

But the STS development lagged while the Skylab's fall accelerated, and by late 1978 it was clear that no STS mission would get into space before Skylab fell out of orbit (which happened in July 1979). Nevertheless, a firmed up (but still troubled) STS rendezvous plan, accommodating the new vehicle's peculiar strengths and weaknesses, had been drawn up, analyzed, and tested in ground simulations. Now there was a "breathing space" for second thoughts on possible modifications to the hastily-developed "double coelliptic" Apollo-style plan.

3: The STS Rendezvous Strategy "Great Debate"

By 1978 it was becoming clear in MPAD that the officially baselined double coelliptic profile was in serious trouble for routine STS rendezvous operations (even while it was marginally workable for the Skylab rescue). MPAD's contractor, the McDonnell-Douglas Technical Services Corporation, conducted plume impingement analyses (by Schoonmaker, Pearson, Chiu, et al.) which were indicating that very delicate maneuvering in the vicinity of gravity gradient stabilized targets was necessary to avoid tumbling the targets. Analyses also indicated that the manual terminal phase could not be performed as designed without drying up the forward RCS tank, since braking required about 40 ft/sec while manual techniques dictated that the Orbiter's Z axis be pointed at the target.

MPAD analysts began efforts to resolve these problems. Several approaches were made.

In one plan, the TPI burn was targeted for a point directly below the target (rather than the target itself), about 1 mile down the radius vector (the +RBAR). There, the "PROX OPS" specialist function was used to target burns so the crew could maneuver the Orbiter up the RBAR by means of "orthogonal braking" logic. This allowed aft propellant (interconnected from the usually "fat" OMS tanks) to be used for much of the approach. Transition to the +VBAR was at 200 ft.

Unfortunately, this profile's timeline was such that sunrise occurred during the climb up the RBAR, and it was orbit noon (sun overhead) by the time the Orbiter got to within 200 feet. The VBAR transition then occurred with the sun in the crewmen's eyes, and VBAR arrival occurred near sunset. This was unacceptable.

In another plan, McDonnell-Douglas analysts (Kelton Jones and Roger Kerr) studied decreasing the coelliptic ΔH, in order to reduce the terminal phase cost. But as the ΔH shrunk from 10 nm to 5 nm, they found that the potential TPI time slips increased from +/- 8 minutes [worst case] to as great as +/- 15 minutes. This also could result in unacceptable lighting conditions for manual terminal phase.

The Concept of STS "Stable Orbit Rendezvous" (SOR)

These problems provided an opportunity for clever creativity. MPAD's Ed Lineberry, who had worked on the Gemini's coelliptic rendezvous profile fourteen years earlier, suggested that the ground should be capable of getting the Orbiter within radar range. Several Gemini rendezvous profiles had done exactly that.

In that case, the plan became to aim for some point directly behind the target (8-10 nm) at the same altitude, and stop there to wait for appropriate lighting. At orbital noon, the chaser performs a near one-rev transfer to intercept, using the radar (with star tracker as backup), aiming at either a close leading VBAR point, or the target itself. Closure rates during manual braking would be small (on the order of 4 ft/sec instead of 40), so the resulting plume impingement and forward RCS consumption would be acceptable.

The stopping point on the trailing VBAR is now known as "transition initiation" [it is abbreviated "Ti", with the small letter chosen to avoid confusion with the targeting spec function's "T1"]. "Transition" implies the change from point-to-point maneuvering to the final, "collision course" trajectory. The range was initially selected to be close enough for radar tracking, but not so close that the target was too bright or too wide for precise star tracker observation.

One variation of the terminal phase was for the Orbiter to aim for an offset point 5000 ft ahead and 1000 ft above the target, with arrival there just at orbital noon, and then manually fly a "glide slope" towards the target. This further reduced plume impingement by utilizing orbital dynamics forces for braking. Some analysis at McDonnell-Douglas (Pearson and Alexander) refined this strategy and performed detailed Monte Carlo dispersion analyses to verify its integrity under nominal and contingency situations. However, the direct approach to the target (with braking and transition to the VBAR at a planned range on the order of 500 ft) was later found to provide adequate plume protection and propellent economy. Direct approach also maintained the classic (Gemini and Apollo) inertial-line-of-sight manual terminal phase procedures, particularly important for radar fail cases.

The Tuned Coelliptic Rendezvous (TCR) Profile

Paul Kramer, who had worked rendezvous procedures since 1962 for the astronaut office, was by this time with the Avionics System Division of the Engineering and Development Directorate (E&D). He was responsible for Orbiter guidance, navigation, and control systems verification, including rendezvous capabilities. In this role (and independent of MPAD), he assembled a team of engineers (from JSC's E&D and from the Charles Stark Draper Labs in Cambridge, Mass.) to also look into possible solutions to the STS rendezvous problem.

After some analysis, they proposed a variation to the double coelliptic rendezvous profile which had long before been baselined and then tailored for the Skylab reboost. This was called the tuned coelliptic rendezvous (TCR). It continued to use onboard navigation and guidance software to support trajectory control operations on the day of rendezvous. A series of Lambert-targeted maneuvers were interspersed with star tracker and radar navigation passes to place the Orbiter on a very small coelliptic segment (ΔH was just 2.5 nm). TPI and terminal phase were "classic". Draper Labs analysis tuned the profile (by judicious selection of burn times) to keep the trajectory dispersions low and to minimize the critical TPI time slips (which could ruin proper lighting during terminal phase).

The TCR profile was developed under certain guidelines. All maneuvers were targeted onboard, satisfying the autonomy requirements imposed by the STS Program Office. Maximum navigation range was about 150 nm. There was to be at least 15 minutes between any navigation completion and the time for a targeted burn (for example, radar lock-on was to occur at least 15 minutes prior to TPI). Post-TPI there would be two midcourse corrections and the terminal point was 1000 ft ahead of the target, on the VBAR, with a closing rate of 0.1 ft/sec.

The TPI Orbiter-to-target elevation angle was 27.5° (little change from Apollo) but changing the orbit travel from TPI to braking to 160° reduced terminal phase ΔV. Reducing ΔH for the final coelliptic phase to 2.5 nm provided radar lock-on prior to TPI and provided overlap in star tracker and radar navigation. Changing the altitudes and trailing displacements of the phasing burns reduced their vertical components and located the second phasing burn within star tracker navigation range. Changing the times between maneuvers located the plane change after the first navigation period, provided two navigation periods prior to the coelliptic burn, and decreased the sensitivity of the TPI burn to any earlier burn dispersions.

The "tuning" of the original STS "double coelliptic" profile used onboard targeting software to bring the Orbiter up to its desired first co-elliptic point through a series of maneuvers in which inefficient but unavoidable RBAR components were combined with necessary large VBAR components (thus getting the RBAR action almost for free since the actual burn was a vector sum of the two right-angled components). And star tracker navigation was applied to targeting and performing each of these burns as early as possible.

The "Great Debate"

When the two independent design teams first clashed in 1981, MPAD's argumentation for SOR originally focussed on three claimed advantages over TCR. SOR was to provide performance improvement (less propellant), operational simplicity (less complex procedures), and freedom from the need for using the star tracker as a navigational aid in nominal cases (and anywhere pre-Ti). In addition, the TCR profile was criticized as exhibiting undesirable instability once the coelliptic orbit was established; that is, it was a dynamic, time-critical situation which required precise crew action to make work. In contrast, SOR would provide a trajectory which allowed for delaying the approach at several convenient points, as might be required by Orbiter or target contingencies.

Considering all the potential rendezvous initial conditions (from above, from below and behind, from behind on the VBAR), SOR also seemed to provide more uniform final profiles. This would greatly simplify crew & ground training, as well as both onboard and MCC software requirements.

However, as the profiles evolved, many of the early MPAD promises for SOR faded. Once workable SOR techniques were developed and tested, they no longer offered clearcut performance advantages over the improved ("tuned") coelliptic profile for standard ground-up profiles. Man-in-the-loop tests in Orbiter simulators also showed that the amount and complexity of SOR crew activity was not distinguishably less than TCR. And in the end, star tracker navigation became routinely necessary as well for SOR.

Furthermore, the SOR was not the only profile with a delay option: if a delay was required, there were also some options (equi-period football) with TCR, but at a fairly high propellant cost and procedural impact. The importance of this criterion may have been overrated at the time. After ten years of flying STS, no rendezvous delay has ever been required.

A major strength of the Gemini/Apollo coelliptic technique was the manual backup to performing the TPI burn, in which the loss of the chaser vehicle's attitude reference or onboard targeting capability could be tolerated by relying on the crew observing the target against an inertial starfield background. For STS, triple redundancy of sensors eliminated the attitude reference concern. The SOR equivalent to Apollo's TPI burn on elevation angle was the second midcourse burn on elevation angle. This burn wound up in darkness (it was already in darkness on the STS/Skylab double coelliptic profile developed in 1977), so the crew wouldn't be able to see the target anyway. So the old manual backup techniques were no longer feasible.

The fact that navigation use of radar data was no-fault tolerant (it could be lost via a single point failure in one MDM) was known, and this made some analysts wish there were more manual backups. However, STS navigation and guidance redundancy has performed well in the first ten years of operations so the pressing need for such manual backup procedures has not been established.

Analysts from Kramer's office continued to criticize many aspects of MPAD's SOR plan. Together with the normal process of procedural evolution, this resulted in significant changes which greatly improved the SOR profile. Most of E&D's concerns in 1981-3 were eventually accommodated by modifications to the MPAD plan; on its own, MPAD's NASA/contractor team was refining the initially raw procedure, e.g. by adding a rev prior to Ti for better planar control.

One of the criticisms leveled at the SOR profile involved the alleged inefficiency of its use of onboard navigation. Routine star tracking was added in late in the development, and the first star tracker pass was not used to correct the trajectory (the first onboard targeted burn follows the second star tracker pass, one rev later). This let state errors propagate longer than necessary, theoretically threatening to increase required trajectory corrections and also threatening to make the second star tracker pass more difficult.

As it turned out, ground navigation proved to be adequate to set up the star tracker passes and these concerns were not proved out. And in 1985 the STS 51-I mission (a "classic" SOR profile) did use the first star tracker pass to provide data for ground targeting.

In general, SOR relied more heavily on ground navigation, and didn't meet the autonomy concerns that E&D was pushing based on its interpretation of STS program requirements. Kramer's group expressed great concern that certain aspects of STS operations involving demonstration of autonomous rendezvous (promised in early STS Level II requirements documentation) would not be validated by the SOR profile. While true, this fact lost significance when flight computer size limits forced scrubs of onboard targeting capabilities. And other early STS rendezvous features -- such as the use of target-mounted transponders as navigation aids -- also were never tested or utilized, once real operations approached.

Some E&D-sponsored analysis also raised questions about the sensitivity of SOR to trajectory dispersions. And indeed, dispersion studies done for MPAD by McDonnell-Douglas confirmed a problem: the plane change after Ti could be up to 5 ft/sec due to ground tracking uncertainties as the Orbiter arrived at Ti. To reduce this uncertainty and resulting large out-of-plane component, the SOR profile was modified to include an extra loop prior to Ti. During this new phase, star tracker navigation improved knowledge of the relative state, and an additional Lambert-targeted burn tweaked the trajectory to better place Ti in plane. This star tracker pass had to begin at orbit noon, so the Ti burn a rev later was forced to occur at about the same time in the orbit.

The Resolution

Final confrontation of the conflicting schools took place at the Rendezvous Flight Techniques panel in 1983-4. The meetings were chaired by Jay Greene, a former MCC Flight Dynamics Officer and by then a Flight Director. MPAD and E&D and their contractor teams argued out the issues. Flight operations personnel (rendezvous procedures were still under the Flight Activities Officer office, while Flight Dynamics was separate) were divided on the subject. The Astronaut Office came down instinctively on the adage, "If it ain't broke, don't fix it", even though in reality the coelliptic scheme had never been tried for STS (it had worked very well for Gemini and Apollo but many things WERE different for STS).

MPAD felt that even with many modifications and the changing rationale, SOR offered benefits. The flexibility of rendezvous delay capability became more important in the arguments. SOR was more efficient for some new STS re-rendezvous profiles. It was also easy to tie in the ground support segment of the early rendezvous activities with the onboard segment (now beginning out at 40 nm), and furthermore there now would be a rev prior to Ti where both ground and onboard navigation and targeting overlapped, allowing them to cross-check each other. Meanwhile, ground support incompatibilities also argued against TCR, since it could not be supported by new software in the MCC (there was no back-to-back Lambert capability). This last item was a big factor in the final decision.

The SOR profile had been developed to bridge the gap between **initial conditions** which promised to be much more variable than those of Gemini/Apollo missions, and a **terminal phase** which was forced by STS Orbiter/target hardware changes to be radically different from Gemini/Apollo proximity operations. While E&D had demonstrated that classic coelliptic ground-up techniques could also be heavily modified to accommodate both end points, and while E&D critiques had highlighted some SOR procedural features requiring improvement, in the end the MPAD recommendation for the SOR profile profile was accepted by the Flight Techniques Panel. The matured SOR profile had absorbed many of the desirable features of coelliptic profiles, and had turned out to retain other attractive features of earlier plans.

After much discussion (the panel minutes are on file), Flight Techniques concurred with MPAD's Stable Orbit Rendezvous profile, as modified. MPAD's NASA/contractor team proceeded to make SOR work for the planned STS-11 target balloon exercise and the STS-13 ("41-C") Solar Maximum Mission flight, and for all subsequent STS rendezvous missions.

Postscript: Following STS-13, Lineberry observed to friends that the realtime need to abort the first Solar Max grapple attempt, fly off and then return later, depended for its success on the efficiency and flexibility of the SOR profile, and that there hadn't been enough propellant to perform the second rendezvous with TCR techniques (no formal proof was ever made, however). The **SOR rendezvous profile**, as modified by several years of constructive criticism, had paid off in front of the ultimate judge and jury, **real spaceflight experience**.
