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SUMMARY OF GEMINI RENDEZVOUS EXPERIENCE

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Abstract

A significant portion of the Gemini program was devoted to the rendezvous problem. One of the major objectives was to establish a base of operational experience and confidence in the required techniques. In this paper, the planning and flight test cycle is reviewed to provide an outline of the Gemini results. Many various considerations were studied and several of the more important factors are discussed as to their influence on the different choices and subsequent operations. The flight test results are summarized according to technique and performance such as propellant costs, satisfaction of conditions, et cetera. Overall, the conclusion is that the base of experience has been established, the rendezvous sequence is practical, the systems and the management of these systems have been satisfactory in accuracy and performance. Further study and a continued, detailed preparation will be the key to the future uses of rendezvous.

I. Introduction

The intent of this paper is to briefly review the rendezvous experience gained in the Gemini flight test program.

From the beginning of the Gemini program, the study and execution of rendezvous techniques have been a major part of our flight test objectives. The interest in rendezvous is based on the required mastery of this operation for the Apollo lunar landing program and as an operational cornerstone for any other potential manned space flight programs. In Apollo, as is probably well known, the lunar orbit rendezvous and any rescue rendezvous depends upon the type of experience gained in the Gemini program. In Gemini then, the intention was to establish the base of experience with rendezvous required for future planning.

This objective became an integral part of the planning for all Gemini missions as we proceeded from the first manned flight through Gemini 12. On the first few flights, we planned to exercise the spacecraft systems and flight crews to build up to the later rendezvous. Gemini 3 provided the first test of the maneuver and guidance capability in orbit. Our first station keeping exercise was attempted on Gemini 4. A closed loop radar-guidance system test with a rendezvous evaluation pod was planned on Gemini 5, but was deleted in flight because of other problems. The Gemini 7/6 flight of the two manned vehicles represented the first operational rendezvous. This capability was extended to docking with an Agena on the Gemini 8 flight. Gemini 9 compressed the time scale one orbit in arriving at the target docking adapter and then performed two different types of re-rendezvous with the same target vehicle. After the initial rendezvous with the target Agena, Gemini 10 used both the Agena and its own maneuvering capability to rendezvous with a completely passive Agena, which was placed in a higher orbit after its use on Gemini 8. A very rapid rendezvous, less than one orbit, was accomplished on Gemini 11, followed by a re-rendezvous later in that flight. Gemini 12 achieved rendezvous in approximately three orbits with a failure in the radar system.

All of these flights contributed a great deal in establishing the required base of operational experience and confidence in the rendezvous technique.

II. Rendezvous Development

During the planning for the rendezvous, a very large number of factors were considered in arriving at a basic plan for the first several rendezvous flights. For our purposes here, it will be useful to consider some of the more important considerations which lead to various choices:

- Launch windows and recycle capability
- Performance characteristics of both vehicles
- Desired terminal phase conditions
- Systems performance
- Considerations for the ground tracking intervals and flight crew procedures

These and other factors represented different types of problem areas which were concurrently studied in the planning cycle. These problems were studied in the broad context of a comparison between three different schemes of rendezvous:

- Direct ascent
- Tangential
- Coelliptical

The salient features of each of these three schemes are represented on Figure 1 in Agena centered curvilinear coordinates.

It was found that some considerations were relatively insensitive to the choice between the three schemes, while others were a very strong function of the technique. Our study effort, then, was oriented towards achieving the best compromise of all of the major considerations maintaining the maximum probability of success for the basic rendezvous plan.

On the subject of launch window and recycle, the

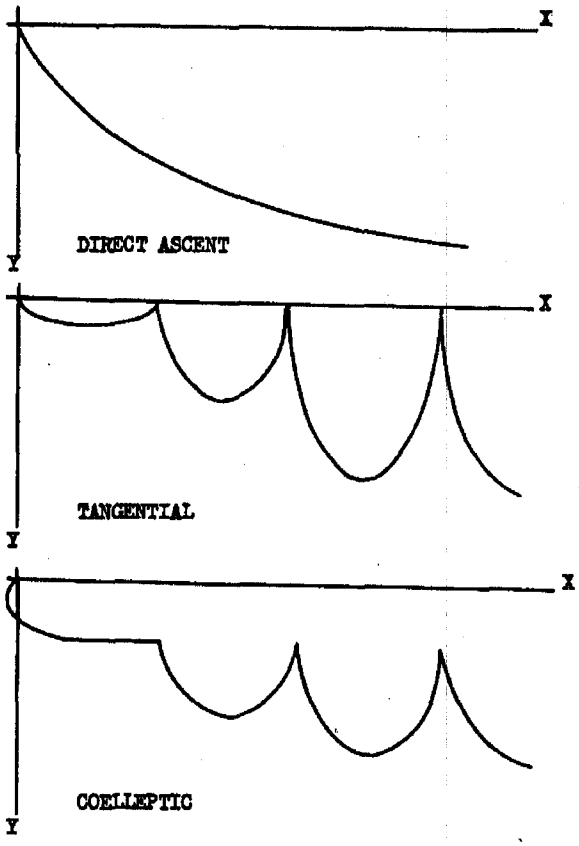

Figure 1

problem amounted to finding a combination of target vehicle inclination and altitude which would provide a sound operation for the planned and subsequent days. It should be noted that, early in the planning, the simultaneous countdown of both vehicles with launch on the same day was introduced and selected. This choice influences the launch window discussion to a certain extent, but was primarily selected for other reasons. At the beginning of the planning, the Agena systems' life was planned around five days, and the spacecraft around two days. This fact and other orbital mechanics consideration lead to launching the Agena target vehicle first. In order to have as many launch opportunities as possible, a same-day launch looked desirable. Also, the Mercury experience withthe difficulty of manned vehicle countdowns leads us to the philosophy of having the manned vehicle in as flight-ready a condition as possible at the time of committing to the Atlas-Agena launch. Besides having the hardware in this launch condition, the uncertainties of weather were also minimized by launching on the same day.

In selecting the target orbit inclination, we desired to have launch window opportunities over five days with a reasonably small out of plane condition. An inclination slightly greater than the latitude of the launching site provided this feature. This inclination was established by launching the Atlas-Agena on a launch azimuth slightly north of east. The spacecraft could then be launched from the Cape at various azimuth on the same and subsequent days over a fairly long period of time (135 minutes) each day while the target orbit was not very far removed from the position of the launch site. This provided the first requirement for a launch window, i. e., an opportunity to launch close to the target plane with an acceptably small performance penalty. Figure 2 illustrates this situation.

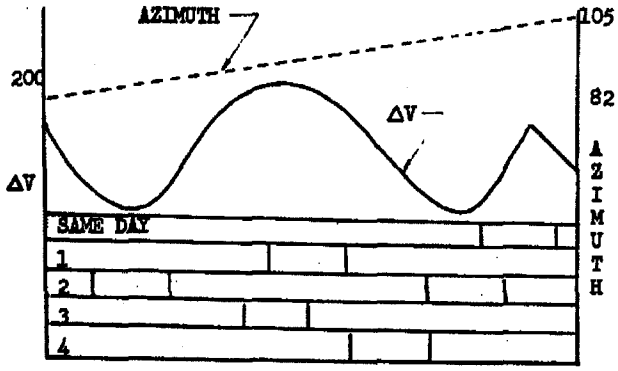

Figure 2

With the 135-minute opportunity, the phasing of the target vehicle with respect to the spacecraft at launch is determined by the target vehicle altitude. The length of flight time which is usable for orbital catchup then establishes the duration of the launch opportunity. For example, after the Atlas-Agena launch, the target vehicle will be very close to in plane with the launch site one orbital period later. A target altitude of 161 nautical miles circular provided a reasonable repetition of launch opportunity on subsequent days also.

The terminal phase (approximately the last 20-30 miles) represented an area of considerable study and planning. It is in this area where the gross vectoring of the two vehicles to a reasonable proximity is accomplished and the transition to the relative sensors and techniques (radar, visual) occurs. In a sense, this is similar to the cross country navigation versus the approach and landing problem for aircraft. Given the assumption that the ground-based vectoring could establish a specified relative condition, what would be the optimum setup for the onboard closure? The solution to this problem entailed setting up the approach trajectory to satisfy a number of considerations:

- A relatively consistent approach trajectory for ease of pilot monitoring
- An approach with a minimum sensitivity to dispersions
- An approach which would permit the use of rather simple onboard techniques to back up equipment failures

Figure 3 represents the terminal phase situation for the co-elliptical approach. It was found that this form of terminal phase satisfied essentially all of the requirements on the terminal phase.

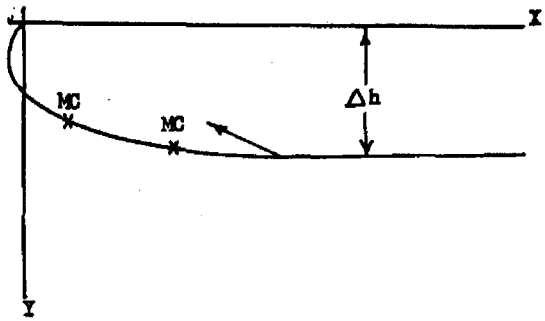

Figure 3

The approach trajectory always looks essentially the same in attitude history, line of sight rates and maneuver sequences. The sensitivity to dispersions was much less than in the other two flight plans, the direct ascent and the tangential method. The selection of the travel angle during the terminal phase (on the order of 130°) provided a reasonable time line for backup procedures, provided the capability for initiating in sunlight, using the flashing lights and the star background for the approach and the braking and dispersion in daylight. It was also found that the maneuver to initiate the terminal phase was along the line of sight to the target and the magnitude is essentially proportional to the physical geometry. These and other pilot-oriented desirable features of this approach were the primary reasons for the selection of the co-elliptical type of flight plan.

The performance and capabilities of the systems were a continuing iterative input to the planning cycle. Radar ranging, accuracies and propellant quantity continued to effect the details of the planning to varying extents. For example, the logic for deciding to use the Agena for all plane changes above a certain value depended upon the amount of Gemini propellants. Accuracies of the guidance system were a major factor in selec ing the number of midcourse corrections in the terminal phase.

To achieve the maximum probability of success, the intervals between ground tracking opportunities and the maneuver sequence had to be evaluated and woven into the overall plan.

Based on these and the other factors, the mission planning cycle arrived at the 4-orbit rendezvous plan. The relative motion of this plan is shown in Figure 4.

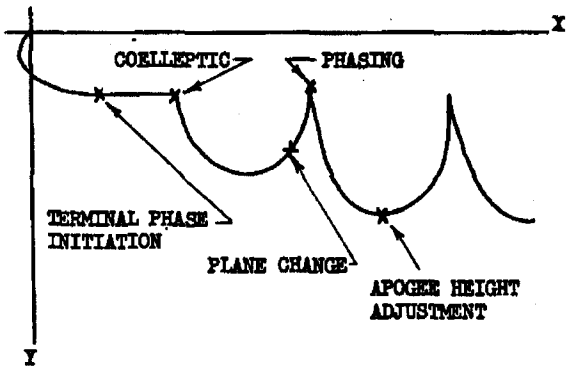

Figure 4

MISSION	TYPE, ORBIT	Δh, MILES	PROPELLANT USAGE POUNDS		LIGHTING AT TERMINAL PHASE INITIATE		LIGHTING AT BRAKING	
			Preflight	Actual	Desired	Actual	Desired	Actual
7/6	4	15	290	325	1 MIN AFTER DARKNESS	3 MIN AFTER	.5 MIN PRIOR TO SUNRISE	1.5 MIN AFTER SUNRISE
8	4	15	290	335	1 MIN AFTER DARKNESS	10 MIN AFTER	.5 MIN PRIOR TO SUNRISE	8.5 MIN AFTER SUNRISE
9	3	12.5	285	290	3.5 MIN PRIOR TO DARKNESS	5 MIN PRIOR	5 MIN PRIOR TO SUNRISE	6.5 MIN PRIOR
10	4	15	305	585	3.5 MIN PRIOR TO DARKNESS	5.5 MIN PRIOR	5 MIN PRIOR TO SUNRISE	7 MIN PRIOR
11	1	10	350	400	8 MIN AFTER DARKNESS	10 MIN AFTER	3 MIN AFTER SUNRISE	5 MIN AFTER
12	3	10	300	295	11 MIN PRIOR TO DARKNESS	6.5 MIN PRIOR TO DARKNESS	12.5 MIN PRIOR TO SUNRISE	8.5 MIN PRIOR

TABLE 1

The salient features of this scheme are:

- No spacecraft maneuvers during the first orbit to allow spacecraft checkout
- A planned point to correct any dispersions from either of the two launch vehicles (lift-off time, altitude, out of plane)
- The terminal phase initiated from a coelliptical orbit 15 miles below the target orbit

In terms of understanding our later rendezvous flights, it is useful to keep this plan in mind. The 3-orbit rendezvous is essentially a compression of this scheme; the 1-orbit rendezvous is a scheme for correcting most of the dispersions before terminal phase, and only had a 2-second launch window since there was noplace to correct for lift-off time dispersions. The terminal phase decisions have been substantiated and exercised on all the flights. Also, the characteristics are generally the same although the geometrical scale is different for various reasons. The re-rendezvous operations were further flight tests in evaluating other aspects of ground vectoring and terminal phase capabilities.

III. Flight Results

With the 4-orbit plan as the basic technique, the primary rendezvous sequences for each flight except Gemini 11 were rather minor modifications of that baseline mission. The objective of rendezvous in the first orbit on Gemini 11 resulted in a compressed plan designed to set up the required conditions for the initiations of terminal phase at the first apogee. On different missions, several re-rendezvous exercises and a dual rendezvous with another Agena were conducted. All of these will be discussed in the following section.

As a resume of all the rendezvous experience, Table 1 is a gross summary of some of the more significant features of each flight. This reference table will be useful in our further discussions of each individual flight.

- The type of rendezvous, 4-orbit, 3-orbit, 1-orbit as an indicator of the basic maneuver sequences
- The light conditions at terminal phase initiation and braking
- The total propellant costs, actual and best preflight estimate.

Notice the different types of maneuver sequences which have been flown. A 2-orbit rendezvous sequence had also been studied for awhile for Gemini 12. It was found the various requirements for guaranteed range for radar lockon and the desired lighting created a situation where the accuracy of the radar system was not sufficient to detect and correct small launch dispersions quickly enough. The differential altitude variation is a measure of the scale of the terminal phase. Since this coelliptic orbit period provides some of the phasing for the terminal phase, the lighting becomes more sensitive to dispersion as the differential altitude (Δh) is reduced. However, a 10-mile Δh has been used extensively and accurately; a value of 7½ miles was used on the Gemini 10 passive rendezvous. The experience is that ground vectoring and certain onboard vectoring techniques can establish the Δh and subsequent lighting fairly accurately. Notice the desired versus actual lighting conditions attained. Notice also the different lighting requirements. These are an indication of the crew ability to handle a wide range of lighting conditions. Propellant costs are also a key measure of the success in rendezvous, since that will continue to be a very precious commodity. These are some of the main features which should be noticed as the individual flights are discussed.

The Gemini 7/6 mission, as flown, was a unique result of the loss of the Agena target vehicle on the first rendezvous attempt, and the availability of the Gemini 7 spacecraft as a target for rendezvous. At the time of the Agena failure, the Gemini 6 spacecraft and launch vehicle were completely checked out and ready to launch. The schedule for the next Agena launch was uncertain because of the need for analyzing and possibly modifying the Agena stage. The Gemini 7 mission then became a logical target for the conduct of a rendezvous exercise, albeit without the possibility of docking. With the addition of the radar transponder on the 7-spacecraft, the rendezvous plan remained unchanged, although the removal of the Agena vehicle with its large capacity for maneuvering increased the necessity for an accurate launch.

Eight days after the Gemini 7 launch, the Gemini 6 vehicle was counted down, ignited and then shut down when an electrical connector plug disconnected. Three days later, eleven days after Gemini 7 lift-off, Gemini 6 was launched on its rendezvous mission. This launch operation must be viewed as a tremendous achievement by the launch team organization.

The maneuver sequence is described in relative motion coordinates in Figure 5.

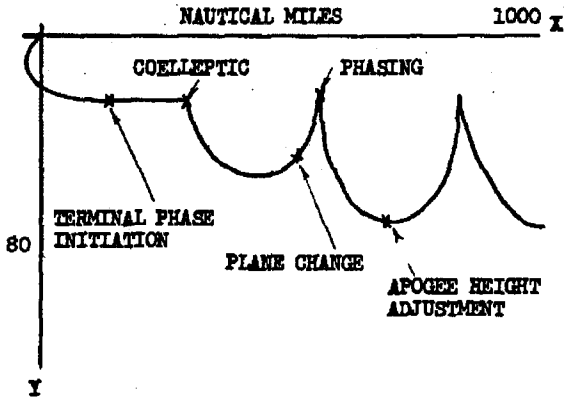

Figure 5

The sequence was essentially nominal with a slightly larger plane change maneuver than on subsequent missions. There were no unexpected occurrences on the rendezvous and the flight test results verified the planning and training activities. Propellant costs were reasonable throughout the sequence,

325 pounds total, and 190 pounds for terminal phase. It was also found that, for comfortable station keeping, the relative range must be maintained at values less than 100 to 200 feet.

The Gemini 8 sequence was essentially a repeat of the previous mission and the first rendezvous with the Agena target vehicle. Both vehicles were counted down simultaneously and launched on the same day, March 16. The sequence is in Figure 6.

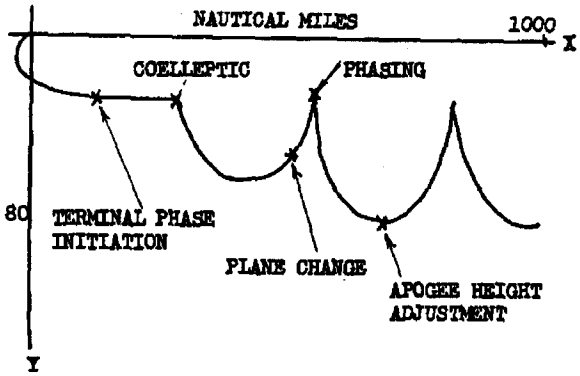

Figure 6

The maneuvers were close to nominal, 335 pounds for the total sequence and 160 pounds for the terminal phase. Again, the operation verified the preflight numbers and docking was also reported to be very similar to docking trainers on the ground. The reflected light from the Agena at braking was reported to be very bright and almost uncomfortable, but did not present a problem. The time of the initiation of terminal phase was the farthest removed from the planned time of all the flights because of ground radar data problem, which was reflected in one of the phasing maneuvers. A planned re-rendezvous was performed later on Gemini 9 because of the early termination of the Gemini 8 flight.

After the two successful 4-orbit rendezvous, Gemini 9 was planned as a 3-orbit rendezvous flight. The first launch sequence was terminated when a control problem in the Atlas vehicle resulted in the loss of the vehicle before booster engine's cutoff. At this time, a specially designed vehicle, the augmented target docking adapter (ATDA), was prepared for launch. This vehicle had been contracted for and built after the loss of the Agena on the first Gemini 6 launch attempt. The ATDA was a non-propulsive stage with most of the other equipment capabilities of the Agena, i.e., the docking mechanism, control system, electrical system, communication and command system. On June 1, the ATDA was placed in a 161 circular orbit by the Atlas. The Gemini count progressed to within two minutes of lift-off when the guidance targeting update from the radio guidance facility was not received. This caused a scrub of the launch.

Two days later on June 3, and with more backup computing for the targeting update, the Gemini vehicle was launched on the rendezvous flight. Telemetry indications from the ATDA warned of a strong possibility that the shroud mechanism was still attached and covering the docking cone. The flight plan would be modified in real time based on the pilot confirmation of the shroud condition. The sequence on the primary rendezvous is shown in Figure 7.

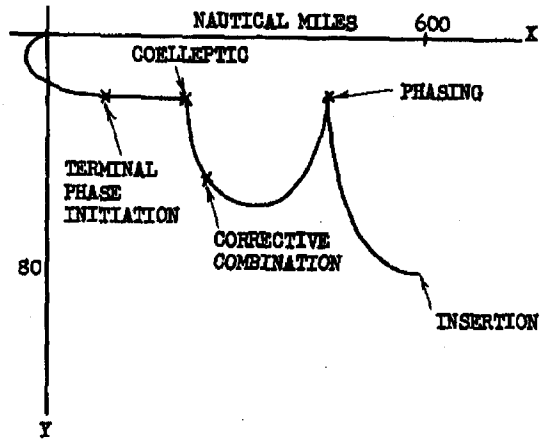

Figure 7

In compressing to the 3-orbit rendezvous, the spacecraft guidance system is used at insertion to trim the orbit dispersions in altitude. A phasing maneuver is performed at first apogee to set up terminal phase conditions. A special set of two maneuvers is then made. The first maneuver, about three-quarters of an orbit after the phasing maneuver, is a combination maneuver to adjust small dispersions in phasing, height and out of plane. The next maneuver (H_{sp}) established coellipticity and nulls the remainder of the out of plane velocity.

The 3-orbit rendezvous was successful and, again, the flight parameters were as expected. The total sequence of maneuvers through station keeping cost and terminal phase for the Δh of 12 miles used 290 pounds of propellants. With the confirmation that the shroud was still attached despite attempts to free it, a modification to the original flight plan was made at this time. The re-rendezvous exercise, previously planned on Gemini 8, was conducted with the purpose of evaluating the lighting and approach on a simulated-passive target. This type of exercise was planned as a step in the preparation for the passive rendezvous scheduled for Gemini 10. The re-rendezvous was a simple one in that a radial maneuver of 20 fps was made resulting in a return to the target vehicle one orbit later. The maximum range was 11 miles. No special problems were encountered in this sequence.

After this exercise, another re-rendezvous was set up for the following day of the flight plan. This called for an approach from above with braking in daylight to simulate the lighting environment in the case of an abort during the powered descent of

the Lunar module. The phasing maneuvers were computed on the ground and performed nominally. The terminal phase was conducted from 7.5 miles above the target. Propellant costs were reasonable at 137 pounds. The lighting conditions were difficult for pilot monitoring and interpretation in that the target was observed against the earth background, (with scattered clouds) and the relative motion appeared to be very fast. This approach precludes the line of sight control visually because of the lack of a reference. A spacecraft configuration change which had been planned and then implemented on Gemini 10, was designed to provide a more accurate reference with the platform-computer combination than the eight-ball display. This feature, called the inertial needles, is simply the option to display on the flight director needles an error from a selected inertial angle. For any lighting or background condition, this would provide an accurate display of the inertial line of sight travel. However, the Gemini 9 experience indicated that approach from above could be troublesome, especially if the visual reference had to be used in the event of equipment failures.

The Gemini 10 mission was a dual rendezvous flight in which the launch timing and planned maneuvers sequence had to be arranged to first accomplish the Gemini Agena rendezvous and then use the Agena and Gemini propulsion to achieve a rendezvous with the "dead" Agena from the Gemini 8 mission. The primary rendezvous was planned essentially the same as the 4-orbit missions of Gemini 6 and 8. This was used in order to provide a demonstrated rendezvous technique and the proper timing to attempt an exercise of additional onboard capabilities. Until this time, the ground complex had provided the maneuvers for the vectoring to terminal phase conditions. Gemini 10 included an operational exercise to evaluate the onboard computations of this maneuver sequence. The phasing maneuvers were computed against the supplied Agena vector with the spacecraft vector from the inertial guidance system and then updated by star sightings. Probably the most significant feature of the primary rendezvous was the propellant usage in the terminal phase which was considerably higher than previous flights. During the final visual phase of the terminal phase, the vehicles were on the order of one-half mile out of plane which resulted in the expenditure. This experience renewed the interest in the sensitivities and possible fuel costs in the terminal phase. It also again demonstrated that it is expensive to drive out dispersions which are of a magnitude to be properly an "orbital-mechanics" problem.

The phasing maneuvers were performed, based upon the ground tracking and computations of the relative orbits of the Gemini-Agena combination and the 8 Agena. The terminal phase was set up at a Δh of 7.5 miles; initiation occurred approximately halfway through the daylight pass in order to have an observable target several minutes before initiation. The transfer angle of the terminal phase was 80° in order to allow braking and station keeping before darkness. The propellant costs were approximately 180 pounds compared to a preflight estimate of 160 pounds.

Gemini 11 was planned for a rendezvous in the first orbit in order to explore that end of the spectrum. Based on timeline and accuracy studies, a trailing displacement in x and y was established as an aiming condition. Prior to this point, the timing of the launch and the corrective maneuvers were designed to meet the desired conditions at spacecraft apogee. At that point, the maneuver to initiate the terminal phase intercept was performed. The relative motion is shown in Figure 8.

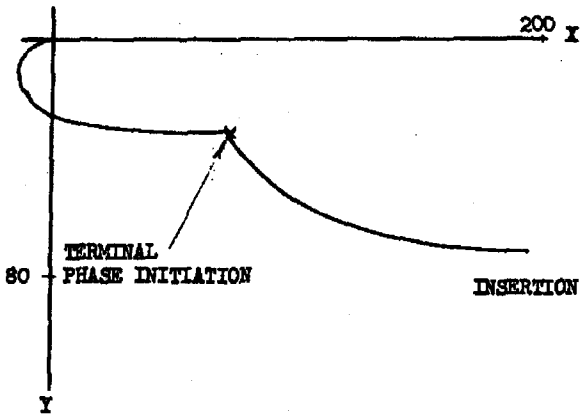

Figure 8

All maneuvers were within expected tolerance and the entire rendezvous sequence was completed for 400 pounds of propellant. This flight demonstrated the equipment and procedural performance which may be required on some lunar abort sequences. Later, a slightly different re-rendezvous was performed on Gemini 11. After separation from the Agena, the spacecraft was vectored to an orbit with all of the same characteristics as the Agena orbit, except that it trailed in position by 15 miles. Over the sleep period, a slight dispersion in the setup caused the two vehicles to separate to a distance of 25 miles. This stable-orbit condition is or interest as a technique for freezing any relative motion and selecting the time of rendezvous on an as-desired basis. This value of range also leads to relatively low closing velocities (~ 10 fps) at braking. The exercise was conducted primarily to determine how well the ground system could vector the spacecraft to braking. The total intercept travel was 292° with both the initiation maneuver and a mid course correction being performed. Without a radar at this time of the flight, Gemini 11 had no difficulty performing the braking and the entire sequence cost on the order of 87 pounds of propellant.

The Gemini 12 sequence was very similar to Gemini 9 which was shown earlier. The most significant feature was the performance of the terminal phase from a Δh of ten miles with no radar. The entire sequence was computed and performed from the radar-fail backup charts. The approximate usage of 112 pounds of propellant is a measure of how well this phase was conducted.

In reviewing the flight record, the propellant costs for the rendezvous missions have been close to nominal. It is useful to look at the two different phases of the sequence, the setup for terminal phase, and the terminal phase itself. The accuracies of the launch vehicles for insertion, and the ground

and onboard systems for the setup vectoring have been very good. The propellants required have been very close to the budget, within a few percent. It has also been the experience that, for any dispersion in the launch phase, the tracking and computing accuracies are very adequate for trimming out such dispersions. Terminal phase costs have been reasonably close to the preflight expected values. This phase is characterized by the requirement for nulling all of the dispersions to precisely zero. For a dispersion which is not large in the setup phase, e.g., .5 mile, a considerable cost may well be necessary in the terminal phase to eliminate that dispersion. Also, the problem is primarily one of orbital mechanics even after the final midcourse is made in the terminal phase and the range is down to one to three miles, depending upon the Δh. Flight results are shown in Figure 9.

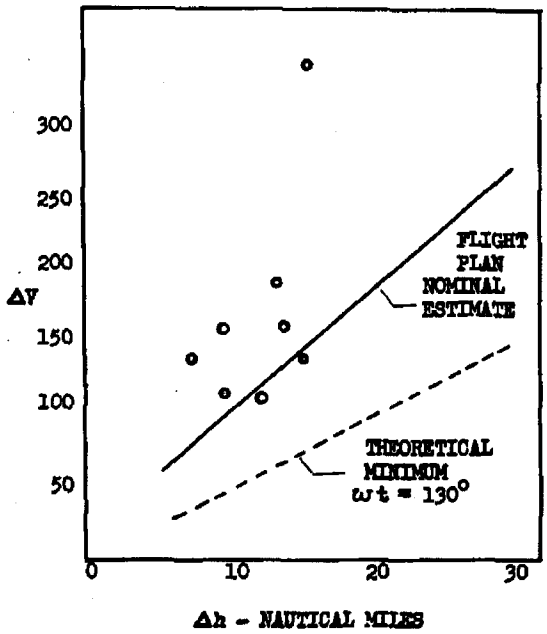

Figure 9

Although these costs are only accurate to perhaps 15 pounds, there is every indication that planning must assume at least twice as much fuel as the theoretical minimum. It is also evident that, for cost considerations, the Δh must be set to some low value, (i.e., a low energy transfer) consistent with the accuracy required for the setup and maintaining an obvious crew indication of positive closing velocities at the braking phase.

In summary then, this rather brief description of the planning and flight test cycle of the Gemini rendezvous missions should provide at least an outline of the program results. Further, it should be stated that the flights have validated the detailed approach in the planning and have given increased confidence in the systems available for achieving the rendezvous, and the ability of the ground and flight crews to manage those systems.

IV. Conclusions

A base of experience in rendezvous has been established in the Gemini program through six different rendezvous flights. Each flight has made various contributions to our knowledge and understanding of this operation. And, from each flight, numerous detailed conclusions and changes have been fed back into the program. In addition, with this first series of rendezvous missions, a number of general conclusions can be drawn:

1. Careful and detailed planning and a buildup in the flight experience has maximized our potential for the performance of the rendezvous missions.

2. Rendezvous is operationally practical as demonstrated by the number of different flight crews and the different types of rendezvous.

3. The ground and onboard systems are very adequate in meeting the accuracy and performance requirements.

4. Continued study and detailed preparation will be the key to success in future rendezvous missions.