6. OPERATIONS WITH TETHERED SPACE VEHICLES

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Introduction

Basically, two modes of tethered space-vehicle operations were explored in the Gemini Program. One mode of operation consisted of intentionally inducing an angular velocity in the tethered system by translational thrusting with the spacecraft propulsion system. The other mode involved tethered, drifting flight during which the effect of gravity gradient on the motion of the system was of interest. These two modes of tethered-vehicle operation will be individually discussed.

Rotating Tethered Vehicles

The tether evaluation in the rotational mode was accomplished during the Gemini XI mission. This exercise was to evaluate the basic feasibility of rotating tethered-vehicle operations as the operations might apply to generating artificial gravity or to station keeping. The exercise consisted of connecting the spacecraft and target vehicle with a 100-foot Dacron tether, and then using the translational thrusting capability of the spacecraft propulsion system to induce a mutual rotation. The result of this mutual rotation was that the vehicles essentially maintained a constant separation at the ends of the tether. Figure 6–1 is an illustration of the spacecraft/target-vehicle tethered configuration.

Analytical Studies

The analytical studies made in support of the rotating tethered-vehicle exercise consisted of two distinct phases. The first phase was a general exploration of the properties of tethered-vehicle dynamics. The second phase consisted of an analysis of the specific spacecraft/target-vehicle tethered configuration of the Gemini XI and XII missions. Primarily, the analytical studies were made using a 12-degree-of-freedom digital computer program. This program numerically integrated the equations of motion of two rigid bodies, each having 6 degrees of freedom and connected by an elastic tether. The program allowed the bodies to have arbitrary mass properties, and the tether attachment points to be arbitrarily specified. The tether was mathematically described as a massless spring obeying a linear force-elongation relationship, and as exhibiting a linear dashpot-type damping property. Since a model for the dynamic behavior of the tether was not included in the analysis, tether motions were not predictable from these studies. In this particular analysis, it was assumed that the only significant external forces on the system were control forces exerted by the spacecraft control system. This assumption eliminated gravity forces which were shown

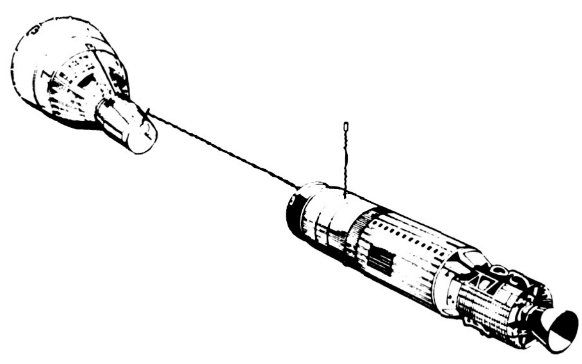

FIGURE 6–1.—Gemini spacecraft/target-vehicle tethered configuration.

to have negligible effect on short-term tether operations such as spinup and despin maneuvers. These studies predicted the dynamic behavior of tethered-system response to initial conditions and to simple, digitally simulated, control-system inputs; however, there was need for a study to reflect the interaction of man with the tethered system.

To supplement the digital studies, a 12-degree-of-freedom, real-time, man-in-the-loop simulation of the tether problem was implemented. This simulation was used to study the effects of pilot real-time inputs into the motion of a tethered-vehicle system by means of an attitude and translational control system. Information about the dynamic behavior of the tethered system was obtained from manual attempts to spin up the system, to control oscillations, and to despin the system.

Properties of tethered-vehicle dynamics.—The first study phase resulted in the establishment of the basic feasibility of the tethered-vehicle exercise. Two rigid bodies connected by a single elastic tether were found to have no alarming dynamic characteristics. The tethered system, however, was found to exhibit oscillational motions that were very complex and peculiar but which could be controlled to some extent with the spacecraft attitude-control system. The most interesting results of the first phase of the study were that tether damping was not very effective for reducing the attitude oscillations of a rotating tethered system, and that tether damping was quite effective in eliminating a slack/taut tether oscillational condition. These two properties of tethered-system motion are illustrated in figures 6–2 and 6–3.

Figure 6–2 illustrates two spinup starts which were identical, except that damping was present in the tether in one case, and no damping was present in the other case. The figure also presents a time history of tension in the tether, and the yaw angle of the spacecraft relative to the target vehicle. It can be seen that while the tension in the tether was strongly affected by damping, the attitude oscillation was relatively insensitive to tether damping.

Figure 6–3 illustrates the effectiveness of tether damping in eliminating a slack/taut tether mode of oscillation. This run started with an initially slack tether that quickly became taut, causing the slack/taut tether oscillation. A time history of the distance between tether attachment points is provided. Since the unstretched tether length was 100

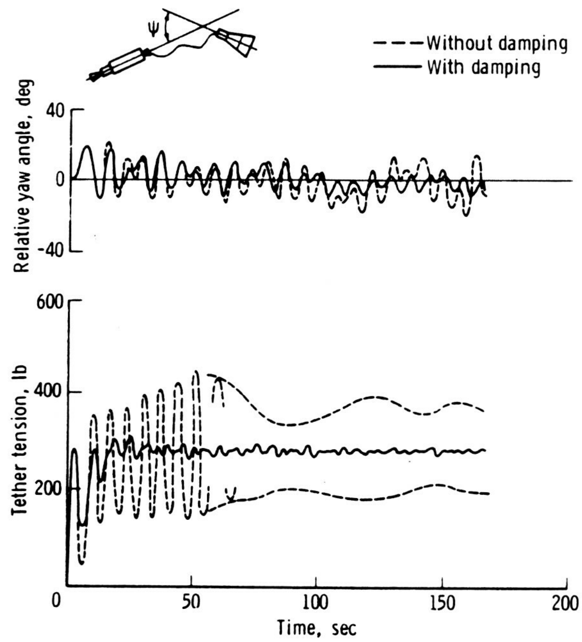

FIGURE 6–2.—Effect of tether damping on the attitude oscillations of tethered systems.

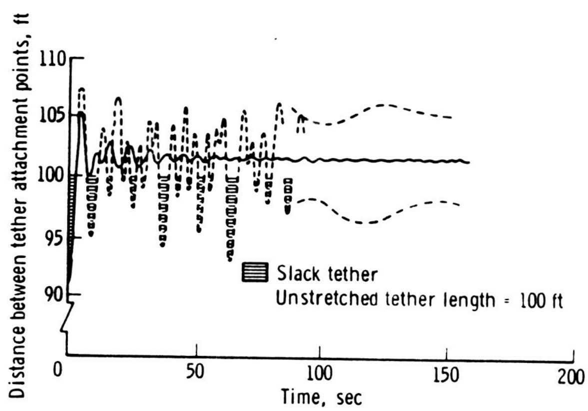

FIGURE 6–3.—Effect of tether damping on slack/taut oscillations.

feet in this run, any time the distance between the tether attachment points was less than 100 feet the tether was slack. It is apparent from figure 6–3 that with no tether damping, the slack/taut condition continued throughout the run; but with tether damping, the slack/taut condition was quickly controlled and resulted in a constantly taut tether condition.

Spacecraft/target-vehicle tethered configuration.—The second phase of the analytical study involved choosing a specific configuration for the spacecraft/target-vehicle tethered system. The selection of a specific configuration primarily involved the hardware and operational aspects. This freedom of choice was possible because the first phase study verified that a rotating tether-system operation was feasible and safe; besides, at this point in time, any possible configuration could be thoroughly studied. The tether length was specified as 100 feet as a compromise between maintaining safe separation of the spacecraft and the target vehicle and for minimizing fuel usage to obtain a given angular rate for the system. The tether size and material were dictated by an early program objective of producing significant artificial gravity effects (high tether loads). The tether spring rate of 600 pounds per foot was intentionally high so the tether could be broken by impact loading as a backup means of jettisoning the tether and the target vehicle if the primary jettisoning procedure should fail. Dacron webbing with a breaking strength of 6000 pounds was chosen as the tether material. The tether attachment points on the two vehicles were determined on the basis of minimum hardware implication on the Gemini Program. Attaching the tether to the spacecraft docking bar also provided a convenient scheme for jettisoning the tether. After it was decided that large artificial gravity effects would not be attempted in the Gemini Program, an 800-pound break link was installed in the tether to lower the requirements on the spacecraft propulsion system for impact breaking of the tether. The final tethered-vehicle configuration was then studied analytically to determine specific dynamic behavior.

Operational Aspects

The operational procedure for spinning up the tethered spacecraft/target-vehicle system consisted of backing the spacecraft away from the target vehicle until the tether was almost taut, then firing the translational thrusters to provide thrust on the spacecraft normal to the line between the vehicles. This imparting of angular momentum to the tethered system generally resulted in a net change in velocity of the center of mass of the system, and subsequently changed the orbit of the vehicles. This effect would not have been present if the system spinup had been accomplished with a pure couple; however, due to the passiveness of the target vehicle in the exercise, the spinup moment on the system had to be supplied solely by the spacecraft translation-control system.

The first complication associated with the operational implementation of the spinup tether exercise involved the fact that the spacecraft lateral translation thrusters had a significant component of thrust in the forward longitudinal direction. As a result, an attempt to spin up the system by firing only the lateral thrusters resulted in a significant closing rate between the vehicles. This closing rate produced an appreciable period of tether slackness, culminating in an extensive slack/taut tether oscillatory mode. The alternatives to this spinup procedure were to orient the spacecraft so that its lateral thrust vector was, in fact, normal to the line between the vehicles, or to simultaneously thrust aft and laterally, thus holding the tether in tension during the spinup maneuver. Both methods had merit, depending upon the degree of spin rate desired for the system. Since the lateral and aft firing technique was applicable in all cases and was operationally simple, it was chosen as the operational technique for spinup of the system. For long-duration spinups, the aft thrusting could be terminated eventually, because the tether would remain taut during the remainder of the spinup due to the motion of the system.

During the spinup procedure, attitude control was required to maintain accurate thrusting to establish a desired spin plane. After the spinup was accomplished, neither the safety nor success of the exercise required further attitude control. Because tether damping did not prove to be an effective means of damping attitude oscillations, active attitude control was required when it became desirable to rapidly reduce spacecraft oscillations. It was found through simulation that the spacecraft control system could effectively reduce the attitude oscillations of the spacecraft; also, when the target vehicle was oscillating, those oscillations would ultimately be propagated through the tether to the spacecraft.

It was evident from the analyses that a differential rolling motion of the spacecraft relative to the target vehicle would probably be excited during the spinup maneuver. This mode of oscillation would be difficult to control with the spacecraft attitude-control system. Probably more difficult to control would be a rolling motion in which the target vehicle and the spacecraft were rolling together. Stopping this latter mode would require inducing a relative roll oscillation so that the tether could be used as a torsional spring which, although weak, would exert a roll moment on the passive target vehicle. Since mild rolling motions would not jeopardize the tether exercise, there was no reason for undue alarm.

From a safety-of-operation standpoint, establishment of a despin procedure was necessary. Such a procedure would enhance the probability of successful jettisoning of the tether at the termination of the exercise. The despin maneuver was essentially the inverse of the spinup maneuver. One procedure for despinning was to locate the spin plane of the system, either visually or with body-rate information available in the spacecraft, and then apply thrust in the spin plane and opposite the direction of spin. An alternative despin procedure involved applying thrust to reduce the line-of-sight rate to zero by visual observation of the spacecraft/target-vehicle line-of-sight motion. The despin maneuver invariably left the target vehicle with residual angular rates when the tether eventually became slack; however, this could be controlled by activating the target-vehicle control system in the despin procedure. An interesting phenomenon was discovered during the operational studies of the despin maneuver. Due to the location of the spacecraft attitude-control thrusters, and to the fact that attitude control of the spacecraft caused translation (the attitude-control moments not being couples), it was possible to automatically despin the rotating tethered system. By activating the rate-command attitude-control mode in the spacecraft and by commanding zero attitude rates, the attitude-control system would attempt to drive the spacecraft body rates to zero and produce a net translational thrust which slowly, but surely, would despin the system.

Crew Training

The crew training in preparation for the spinup tethered-vehicle exercise was primarily familiarization through simulation practice. To provide a realistic simulation of the interaction of two vehicles tethered together, a real-time simulation of the tethered-vehicle system was implemented.

The simulation facility consisted of a high-fidelity crew-station mockup, a planetarium-type projection visual display, and a hybrid-computer complex. The equations of motion describing two unconstrained rigid bodies (6 degrees of freedom per body) connected by a massless elastic cable were solved in real time on the hybrid-computer complex. This mathematical model included the off-symmetrical tether attachment points on the spacecraft and target vehicle, as well as the actual inertia properties of the vehicles. Best estimates of the tether-spring constant and damping characteristics were used for the training simulations. Included in the solution of the governing equations of motion was a simulation of the spacecraft attitude and translational control system. This simulation allowed real-time astronaut control inputs to properly effect the motions of the tethered vehicles. All basic flight instrumentation, as well as engineering parameters, were displayed in real time in the crew station.

The visual presentation consisted of a planetarium-type gimbaled Earth-scene horizon and star-field projection. The visual presentation of the target vehicle consisted of two spots of light from dual-target projectors. The two spots represented the ends of the target vehicle. This presentation allowed a visual recognition of maneuvering relative to the target vehicle, as well as observation of the attitude oscillations of the target vehicle. In flight, the tether would supply a visual cue concerning the separation distance between the two vehicles; however, in simulation, visual representation of the tether was not possible and the cue was supplied by a display in the crew station.

The training simulations usually began with the spacecraft undocked, but close to the target vehicle. The astronaut was then required to translate away from the target vehicle to a tether-extended position where the spinup maneuver would be initiated. After the system achieved the desired spin rate, the astronaut was free to observe the subsequent motions and obtain a feel for the behavior of the tethered system. Attitude control could be attempted in a direct, pulse, or rate-command mode of attitude control. Typical training exercises consisted of intentionally inducing large attitude oscillations in the spacecraft by means of the attitude-control system, and subsequently reapplying control moments to reduce these oscillations. Following these maneuvers, the astronaut could finish the exercise by practicing the despin procedure. Practice in breaking the tether with impact loading was also possible, since tether tension levels resulting from various maneuvers were displayed to the astronaut.

In addition to the crew training usage of the tether simulation, valuable engineering knowledge was gained concerning the general behavior of the tethered systems as well as of the specific configuration selected for Gemini. It was possible to observe in real time the response of a tethered system to very complex forcing functions (that is, inputs by a pilot). Although not directly associated with the flight maneuvers, the functions nevertheless yielded insight into the system behavior. The simulation allowed the design engineer to personally intervene in the scientific solution of the tether motion by way of a control system. The simulation was used to determine system response to control thrusters stuck in the ON position. Before the Gemini XI mission, the simulation was used to determine the effects of a degraded thruster prior to and in support of the actual spinup. Fuel usage for the spinup procedures was also determined in this training simulator.

Flight Results

During the Gemini XI mission, a total lateral thrusting of approximately 13 seconds was applied to the tethered system and resulted in a system spin rate of approximately 0.9 degree per second. Slack taut tether oscillations were induced during the spin following the termination of aft thrusting. This was due primarily to the fact that the tether tension associated with the low spin rate was smaller than the tether tension induced by thrusting aft; hence, at termination of aft thrusting, the tether simply catapulted the vehicles toward one another. After approximately 1½ orbits of the Earth, the spinup operation was terminated with a despin type of maneuver and the tether was jettisoned.

The results of the rotating tethered-vehicle maneuvers during the Gemini XI mission were essentially as anticipated. By comparing the motion pictures of the maneuver taken during the mission with the observations in the training simulation, it is evident that the simulation was quite accurate in predicting the general behavior of the tethered system. The flight crew found that the active damping of oscillations with the spacecraft attitude-control system was easier in flight than in the training simulation. This effect was probably due to the degraded sensory information available to the astronaut in the simulation as compared with the actual flight. It was observed that cable slack/taut oscillations damped out more rapidly in flight than in the simulation. This discrepancy was traced to a conservative value for the tether damping constant which corresponded to a room-temperature tether rather than a cold tether which would have a higher damping constant. As anticipated by analysis, the differential roll motion between the vehicles did, in fact, occur and was approximately to the extent predicted.

An interesting event occurred during the deployment of the tether. Near the end of deployment, a cable-dynamics phenomenon known as the skip-rope effect became significant. This behavior, although obviously possible, had not been predicted by the tether analyses employed in the design of the tether maneuver, since the studies did not include tether degrees of freedom. After the skip-rope mode of oscillation subsided, the spinup maneuver was successfully conducted with no evidence of significant cable-dynamics effects, thus confirming the analytical assumption that cable dynamics were not significant in the rotational behavior of this particular tethered system.

Gravity Gradient

The gravity-gradient tether exercise was accomplished during the Gemini XII mission to study the feasibility of using gravity-gradient effects in the stabilization of manned spacecraft. The exercise consisted of tethering the orbiting vehicles together, then arranging the vehicles one above the other at the ends of the extended tether (that is, along a local vertical). By imparting the proper relative velocities to the vehicles in this arrangement, the vehicles would proceed into a constantly taut tether configuration and the tethered system would be captured by the gravity gradient. This captured behavior would be manifested by oscillation of the system about the local vertical.

Analytical Studies

Analytical studies of the gravity-gradient tether exercise ranged from simple feasibility studies to fairly sophisticated analyses. While the operational feasibility of gravity-stabilized satellites was well established, the stability of two rigid bodies tethered together in orbit was questionable. Therefore, analytical studies were first aimed at exploring the basic behavior of a tethered system in a gravity field, and then at establishing the operational aspects of obtaining a gravity-gradient-stabilized tethered system.

The first feasibility studies were conducted using a mathematical model that consisted of two point masses (each with 3 degrees of freedom) subject to an inverse-square central force field. The two point masses were assumed to be connected by an elastic tether which satisfied a linear force-elongation relationship. The equations describing this system were numerically integrated in a digital computer program to yield time histories of the significant parameters in the analysis. This phase of the analytical study established that at least two point masses could be tethered together and gravity gradient stabilized. This study, of course, had applicability to the actual situation since it could be argued that two rigid bodies connected with a tether of sufficient length would exhibit particle-like behavior. Since there was no effective damping mechanism in the proposed tethered system, and since the gravity-gradient exercise could continue over but a few orbits, the success of the exercise was strictly a matter of giving the tethered system the proper initial conditions. This being the case, the first phase of the study consisted of determining the response of the tethered system to various combinations of initial conditions.

The initial conditions for a perfect start were established; these included a slightly taut tether, and a relative velocity of about 0.138 ft/sec for a 100-foot tethered spacecraft/target-vehicle combination. The perfect start, of course, also included an initial alinement along a local vertical and an approximately circular orbit for the system. Response to the perfect start consisted of continued alinement of the two point masses along the local vertical and of a constantly taut tether. Perturbations to this perfect start involved off-nominal relative velocities which were not compatible with continued motion along the local vertical, or an initially slack tether with or without range rate between the bodies. The tethered point masses were found to be reasonably tolerant of off-nominal starting conditions. For small perturbations, the solutions to the motions of the tethered point masses were in agreement with linearized dumbbell-satellite theory. This point-mass analysis was eventually modified to include an oblate earth as the attracting force on the point masses. This change was found to have negligible effect on the behavior of the tethered system. From the first phase of study, it was concluded that gravity-gradient stabilization could possibly be obtained with the spacecraft and target vehicle in the tethered configuration. Figure 6–4 illustrates typical results obtained from the point-mass analysis on the sensitivity of the system motion to initial relative velocity between the point masses.

The second phase of the analytical studies was conducted using a mathematical model consisting of two rigid bodies in planar motion subject to an inverse-square central force field, and connected by an elastic tether. The equations of motion describing this mathematical model were integrated numerically in a digital computer program to provide time histories of significant parameters. This phase of the study was implemented to answer questions concerning the rigid-body attitude response of the spacecraft and the target vehicle during the gravity-gradient exercise, and to confirm the validity of the conclusions drawn from the point mass analysis. From the results of this rigid-body study, it was found that (1) there was good agreement between the rigid body and the particle analysis concerning capture limits and tolerance to starting perturbations; and (2) there could be considerable rigid-body rotation of the target vehicle and the spacecraft during the gravity-gradient exercise. Figure 6–5 illustrates a typical time history provided by the planar rigid-body analysis. Of importance was the determination that the capture sensitivity of the system was not significantly related to the rigid-body-attitude initial conditions. This fact was certainly welcome from the operational standpoint of setting up a captured system. On the other hand, the large rigid-body excursions of the vehicles would have an operational implication on such things as observation of the total system motion during the gravity-gradient exercise. While this rigid-body study provided valuable information, there were still a few questions concerning the rigid-body response of the vehicles and the stability of the system with all degrees of freedom present.

To answer these questions, a final study phase was implemented. The final phase con-

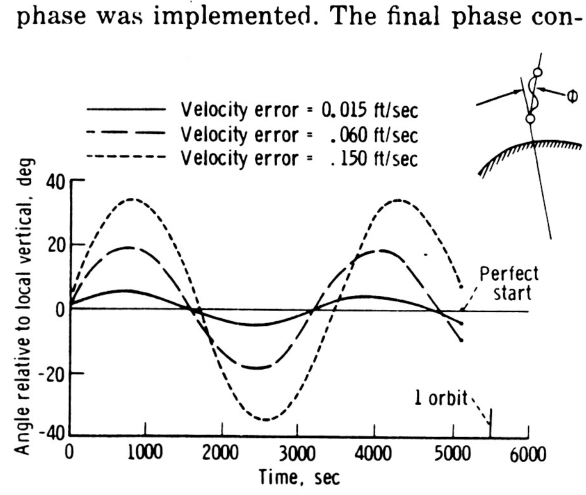

FIGURE 6–4.—Effect of off-nominal relative velocity on motion of gravity-gradient tethered system.

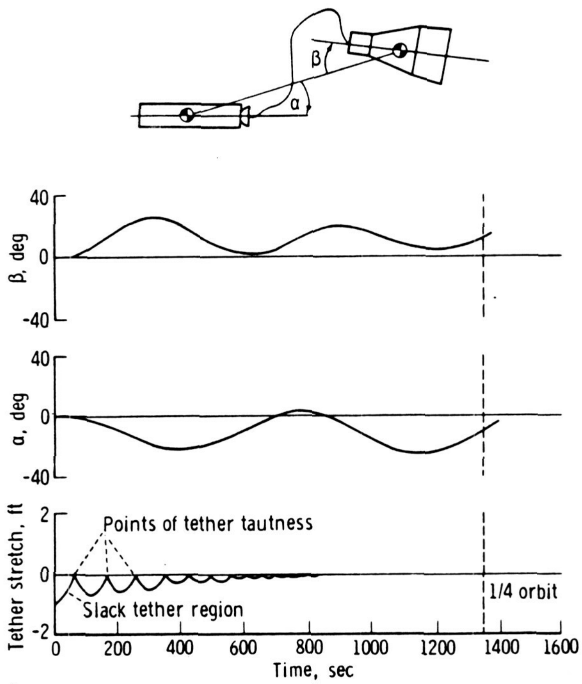

FIGURE 6-5.—Effects on rigid-body attitude response during gravity-gradient motion due to initial tether slackness of 1 foot.

sisted of solving the equations of motion describing two rigid bodies (each with 6 degrees of freedom) in an inverse-square central force field and connected by a linear elastic tether. This study confirmed the applicability of the lesser analyses that had been performed, in that good comparisons of capture limits and response to perturbations were obtained. As expected, the results of the final study indicated that a captured system would still be likely to have large rigid-body-attitude excursions; however, of even more significance, was the finding that there were no unforeseen instabilities in the behavior of the proposed gravity-gradient exercise. This final phase of study was primarily concerned with the spacecraft/target-vehicle configuration which would be used in the mission.

This concluded the analytical study phase of the tethered-vehicle gravity-gradient experiment. With the theoretical validation of the exercise completed, the problem then was to devise an operational technique to provide the proper initial conditions for the tethered system.

Operational Aspects

The objective of the gravity-gradient-stabilized tethered-vehicle exercise was to orient the vehicles one above the other (along a local vertical), and to provide proper starting conditions so that the subsequent motion would, at worst, be a limited amplitude oscillation of the system about a local vertical, and, at best, a continued perfect orientation along a local vertical. The proper starting conditions consisted of a slightly slack tether and a relative velocity of 0.138 ft/sec. Although it was relatively easy to position one vehicle directly over the other with a slightly slack tether, it was much more difficult to obtain a relative velocity of 0.138 ft/sec between the vehicles. A deviation of more than 0.23 ft/sec from the perfect relative velocity would mean that the gravity-gradient torque on the system could no longer contain the oscillations of the system around the local vertical; the system would then cartwheel, or be spun up.

The problem of obtaining the correct relative velocity between the spacecraft and the target vehicle was approached as follows. The perfect initial relative velocity corresponded to that relative velocity which would exist between the separated bodies if they were both attached to the same radius vector from the center of the Earth and rotating at orbital rate. It was decided to make use of this fact in the starting procedure. The capability existed on board the spacecraft to provide information to the flight crew from which the longitudinal axis of the vehicle could be made to coincide at all times with the local vertical direction. By positioning the spacecraft directly above the target vehicle with the longitudinal axis of the spacecraft maintained continuously along a local vertical, deviations from the perfect relative-velocity conditions would be manifested as drift of the target vehicle relative to the spacecraft. This drift could be detected quantitatively by the flight crew using the optical sight, and could be converted to an equivalent drift rate. From the drift rate, the deviation in relative velocity from the perfect start could be determined; hence, an appropriate velocity correction could be applied with the spacecraft translational thrusters. A perfect relative-velocity start would result in a zero-drift rate of the target vehicle relative to the spacecraft, as long as the longitudinal axis of the spacecraft was continuously along a local vertical. Figure 6–6 shows a flight chart from which the flight crew could take quantitative drift measurements (as angular drift in the optical sight) over a measured period of time and find the equivalent drift rate in the form of a relative-velocity correction. The flight chart indicates the expected maximum oscillation of the system from a local vertical for a given error in relative velocity. After the flight crew had ascertained that an acceptable initialization had been accomplished, the flight plan required that all thrusting be terminated and the drifting system observed to determine the success of the initialization. While a perfect starting condition dictated a very slightly taut tether, it was operationally more feasible to start the system with a definitely slack tether, and a zero-closure rate. This was due to the minimal perturbation to, and

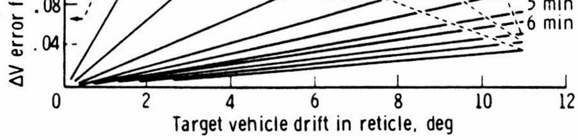

FIGURE 6–6.—Starting procedure chart for Gemini XII gravity-gradient tether exercise.

rapid recovery of the system from, an initially slack tether. The gravity-gradient effects would soon draw the tether taut (this being the stable configurations for the tethered system) for the remainder of the operation. The penalty paid for an initially slack tether was an increase in the angle of oscillation of the system relative to a local vertical.

Crew Training

Crew training for the gravity-gradient tether exercise consisted of briefings and simulator exercises. The significant flight-control task involved measuring the drift of the target vehicle in the optical sight, then applying the proper translational thrust to correct the relative velocity of the vehicles. The training was accomplished in the Gemini Mission Simulator, which had the capability to start a flight simulation run with the spacecraft docked with the target vehicle. The simulation exercise could then proceed with the undocking, followed by a maneuver to reach a position approximately 100 feet above the target vehicle. From this position, the use of the flight chart for the gravity-gradient starting procedure could be practiced. The mission simulator did not include tether dynamics or a visual simulation of the tether. This deficiency did not greatly hinder training for the gravity-gradient exercise, since the cable was not supposed to be taut during the starting procedure. The significant task to be practiced in training was to maintain a local vertical with the aid of the spacecraft instrumentation, and to detect and remove target-vehicle drift rates relative to the spacecraft.

Flight Results

There were three orbits allotted to the gravity-gradient tether exercise on the Gemini XII mission. Approximately half of this orbit time was used in establishing the starting conditions for the exercise. The remainder of the allotted time was spent observing the subsequent motion of the system.

The initialization of the system consisted of various translational and attitude thrusting maneuvers by the spacecraft, and an active stabilization of the target vehicle using the target-vehicle control system. After the flight crew had ascertained that acceptable initial conditions had been achieved, the crew deactivated the target-vehicle control system and terminated all spacecraft thrusting. The resulting motion was one of limited amplitude oscillations relative to local vertical. It was evident that the system was indeed captured by the gravity gradient. After initial perturbations, the tether became constantly taut, and the attitude oscillations of the spacecraft were of sufficiently limited amplitude that the crew were able to view the target vehicle almost continuously. Under these conditions, the target vehicle was never observed to rise toward the horizon by more than approximately 60° from local vertical.

The initialization of the gravity-gradient exercise was greatly hampered because some of the control thrusters on the spacecraft were malfunctioning. Attitude control had degraded to the extent that the preflight planned procedure for setting up the gravity-gradient exercise could not be accomplished. Despite this handicap, the crew was able to devise a backup procedure consisting of judicious use of remaining thrust capability to provide initial conditions for a successful gravity-gradient capture.

The simulation training for the gravity-gradient exercise was adjudged by the crew to present a more difficult problem than the actual flight situation. The crew concluded that, with a properly functioning control system, the gravity-gradient-capture initial conditions could have been accomplished with relative ease and certainty.