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MISSION PLANNING FOR PIONEER SATURN/URANUS ATMOSPHERIC PROBE MISSIONS

by Byron L. Swenson, Edward L. Tindle, and Larry A. Manning

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16. Abstract

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SUMMARY

Mission planning for a series of atmospheric probe missions to Saturn and Uranus using a modified Pioneer spacecraft launched in 1979 and 1980 has been examined. This report summarizes the operational options and the associated systems requirements consistent with the major scientific goals and spacecraft constraints of the missions. In general, it is feasible to obtain *in-situ* atmospheric measurements in the atmosphere of Saturn and Uranus down to a pressure level of 10 bars using a common probe and spacecraft design. Spacecraft can be launched to both objectives with an adequate launch window in 1979 and 1980 using a Titan/Centaur launch vehicle with a TE-364-4 upper stage. In addition to the prime objective of the *in-situ* atmospheric measurements, other scientific objectives can be accomplished by the flyby spacecraft. Encounters with the satellite Titan and RF occultations of Saturn, the ring system of Saturn, and Uranus can be obtained.

INTRODUCTION

For some time, a great deal of attention has been given to various means of exploring the outer planets. Particular interest has been focused on *in-situ* sampling of the atmospheres of the outer planets by survivable probes. This interest is due to the strong scientific feeling that these atmospheres are a storehouse of information on the formation and evolution of the solar system.

Over the past several years, several studies (e.g., refs. 1-3) have examined the feasibility of probing the atmosphere of Jupiter. Unfortunately, the entry thermal environment experienced by a probe entering the atmosphere of such a massive planet at hyperbolic speeds is currently beyond the state of heat-shield technology. Naturally, attention has shifted to the possibility of probing less massive outer planets, namely, Saturn and Uranus. Because Saturn is approximately twice as far from the Sun as Jupiter and Uranus is twice again as far, a small spacecraft of the Pioneer class must be used to reach these objectives with the launch vehicle capability currently available. Thus, the Outer Planets Science Advisory Group of NASA has recommended that the feasibility of a series of Pioneer class missions to be launched to Saturn and Uranus in 1979 and 1980 be considered in greater detail.[1] It was further recommended that the probe be designed to survive to an atmospheric pressure of 10 bars. The series of recommended missions is made up of a single launch in 1979 to Saturn followed by two launches during the 1980 window to Saturn with a subsequent swingby past Saturn to Uranus. The capability to target probes for Saturn is to be retained for both 1979 and 1980.

[1] Mission Building Blocks for Outer Solar System Exploration, by D. Herman, J. W. Moore, and P. Traver (to be published in Space Science Review).

The purpose of this report is to examine in detail desirable launch and targeting options to determine the spacecraft requirements associated with probe targeting, entry, and communications. This information is to be used in conjunction with future systems analysis efforts to establish the feasibility, cost, and programmatic options for this series of missions.

TARGETING STRATEGY

The targeting strategy developed below is a result of balancing five operational factors: heliocentric trajectory selection, aiming considerations at the target planet, probe entry conditions, probe/spacecraft deflection velocity requirements, and the relay communication geometry between the probe and spacecraft. For simplicity, each of these five factors will be discussed in order, but it must be remembered that all these factors are highly interactive. This discussion will be made first for the 1979 Saturn direct mission followed by a similarly ordered discussion for the 1980 Saturn/Uranus mission.

All the heliocentric trajectory analysis contained in this report was obtained through the use of a digital computer program utilizing the patched-conic technique described in reference 4. All operations and geometry within the sphere of influence of a given planet were analyzed from digital computer programs of the three-dimensional motion of a body in a central gravitational field. Planetary ephemerides were obtained from reference 5, Saturn satellite ephemerides were obtained from reference 6, and planetary properties were obtained from references 7 and 8.

1979 Saturn Direct Mission

Selection of heliocentric trajectory– The mission set to be examined consists of a single launch to Saturn in 1979 followed by two launches during the 1980 window to Saturn with a subsequent swingby past Saturn to Uranus. The launch vehicle to be used for these missions is the Titan IIIE/Centaur/TE-364-4. A preliminary estimate of the total injected spacecraft weight is about 480 kg (1050 lb) with an uncertainty of about 20 kg. The injection performance of the launch vehicle for this weight range is shown in figure 1. Injection energies of 140 to 150 km^2/sec^2 can be achieved.

With injection energies in this range, the resulting launch window for the 1979 Saturn direct mission is shown in figure 2. The arrival date at Saturn is shown as a function of launch date at

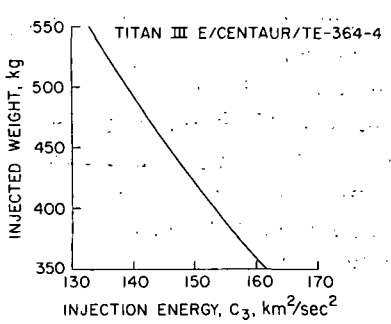

Figure 1.– Launch vehicle capability.

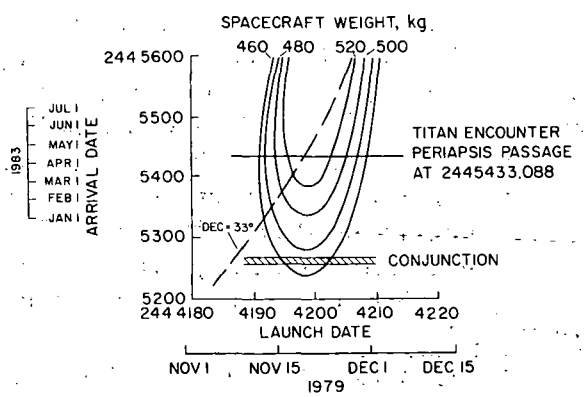

Figure 2.– 1979 Saturn direct launch window.

Earth for several spacecraft weights. The dates are shown for both the Julian and Gregorian calendars. The boundary across the figure indicates a departure declination from Earth of 33°. To the left of this boundary, the departure declination is higher than 33° and thus, with a 108° launch azimuth safety constraint from Kennedy Space Center, a plane-change maneuver is required at heliocentric injection from the parking orbit to achieve the appropriate departure declination. This plane-change requirement results in a small payload penalty which, in turn, causes the payload contours to bend back as apparent in figure 2. It can be seen from the figure that there is a launch period of about 2 weeks for the range of spacecraft weights of interest with a trip time to Saturn of about 3.5 years. Trips to Saturn arriving within a few days of Julian date 2445270 are excluded (as shown by the shaded band) because Earth and Saturn are at conjunction at that time, resulting in a loss of communications with the spacecraft. Since the heliocentric communications range from Saturn to Earth is minimized about 180 days after conjunction and a 2-week launch period is desired, a fixed arrival date at Saturn near 2445430 has been chosen for an injected spacecraft weight of 480 kg.

Because one of the secondary scientific objectives of such a mission is perhaps to have a near encounter by the flyby spacecraft with a satellite, a search was made for such desirable encounters near the chosen arrival date. The satellite of greatest interest is, of course, the largest of Saturn's moons, Titan. Since the approach to Saturn for the 1979 mission is at very low declination to Saturn's equator and the orbit plane of Titan, very good inbound encounters with Titan were found. These encounters occur every 16 days (Titan's orbital period) and the one chosen for this mission results in a periapsis passage date by Saturn of 2445433.088. The encounters with Titan for this arrival date across the launch window are shown in figure 3. The distance from Titan is shown as a function of solar phase angle as seen from the spacecraft. The encounter starts about 400,000 km above the nearly fully lighted satellite disk (phase angle near 0°) and passes over the terminator (phase angle, 90°) at about 150,000 km. Designing for a satellite encounter does not seem to compromise the probe mission objectives in any way, so a fixed arrival date of 2445433.088 was chosen for the 1979 Saturn direct mission. If the spacecraft injected weight were to increase, resulting in a loss in available launch window for this arrival date, later arrival dates in multiples of about 16 days could be used which would have very similar Titan encounters.

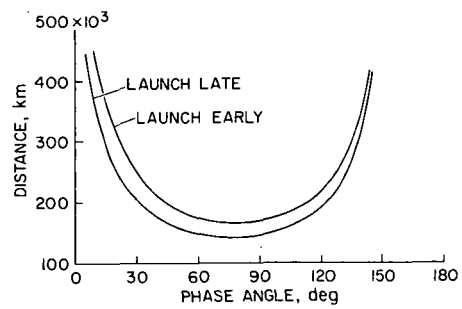

Figure 3.– Titan encounter (Saturn periapsis at 2445433.088).

Aiming conditions– Having chosen the heliocentric trajectory and hence specified the arrival conditions, it is now possible to specify the aiming conditions for the encounter with Saturn. The first and foremost considerations for the aim point specification are that the probe be delivered to a scientifically interesting latitude on Saturn, that the ring structure be avoided by both the probe and flyby spacecraft, and that an attractive communications geometry be maintained between the probe and flyby spacecraft. In addition to accomplishing the probe mission in a near optimum fashion, it is also desirable to accomplish other flyby science, some of which augments the *in-situ* measurements of the probe. Finally, some consideration must be given to post-encounter scientific objectives, that is, where the spacecraft goes after its encounter with Saturn.

The specification and the constraints on the aim point of the encounter are conveniently displayed in the aiming diagram of figure 4. The plane of the diagram is the so-called impact plane or the plane perpendicular to the hyperbolic approach vector at Saturn. The polar coordinate, θ_{aim}, is the azimuth of the flyby trajectory measured clockwise from a vector in the impact plane which is the intersection of the impact plane and the equatorial plane. Thus, for example, for $\theta_{aim} = 0°$, an easterly flyby at minimum inclination results and for $\theta_{aim} = 90°$, a south polar flyby. The radial coordinate on this plane is the periapsis radius of the flyby trajectory. These two parameters, that is, θ_{aim} and the periapsis radius, together with the arrival vector uniquely define the flyby hyperbola.

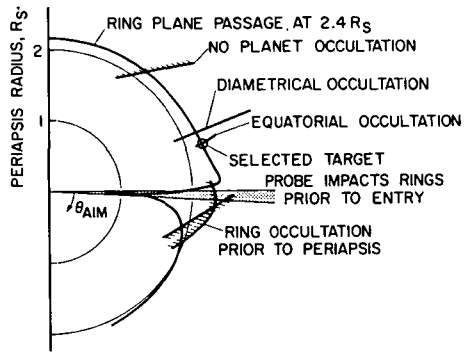

Figure 4.– Aiming diagram at Saturn (1979).

In figure 4, only the right-hand side of the impact plane is shown since only posigrade trajectories are desired to take advantage of the rotation of the atmosphere to reduce the relative entry speed. The first constraint (fig. 4) on the aim point conditions is the near-circular contour near a periapsis radius of about $2R_S$ (Saturn radii) inside of which the flyby spacecraft will pass through the ring plane at a radius of less than $2.4R_S$. A ring-plane passage of $2.4R_S$ was chosen to avoid the visible ring structure, including an allowance for guidance uncertainties. The second constraint is that the probe must not impact the rings before entry. This is shown by the wedge-shaped shaded region near $\theta_{aim} = 0°$. Finally, since the spacecraft is to relay the probe data to Earth, it must not be occulted from Earth by Saturn or the rings before the probe descent to 10 bars is completed. Completion of the probe descent corresponds approximately to the time the flyby spacecraft reaches periapsis. Periapsis radii inside the curved shaded boundary between a θ_{aim} of about 0° to +30° result in ring occultations by the spacecraft before periapsis and are thus excluded. The composite of these three ring avoidance constraints results in a set of aim point conditions for which the probe may be safely delivered to atmospheric entry. The remaining task is to limit this region to a few aim points that deliver the probe to an acceptable latitude, minimize the relay communications problems from the probe to the spacecraft, and that allow secondary flyby science to be accomplished.

One of the most important measurements to be accomplished on the flyby spacecraft is a dual-frequency RF occultation of the atmosphere. Such a measurement should be nearly at the latitude of the probe entry and to reduce the problems of interpretation should be nearly diametrical, that is, the flyby trajectory plane should be nearly edge-on as seen from Earth. This greatly simplifies the analysis of the refractive bending of the RF rays. The straight lines in figure 4 indicate the locus of conditions for diametrical occultation and the boundaries above and below which no planet occultation occurs. The desire for a planet occultation restricts the choice of θ_{aim} to the region between about 0° to −60°.

Finally, it would be desirable to exit occultation from the planet in the region of the equatorial gap between the planet and the visible rings. To aid in visualizing this condition, figure 5 illustrates how such a passage would appear from Earth. Such an occultation exit would provide an unobstructed occultation at the equator and might give some hint as to whether any particulate matter exists in this region. The locus of aim point conditions that provide such an equatorial occultation is shown in figure 4.

Therefore, a highly desirable aim point is found at the intersection of the equatorial occultation locus and the ring avoidance contour. This condition (labeled circle) provides a probe entry latitude about 20° north, nearly diametric occultation at about 20° north, an equatorial exit to the occultation, and a minimum communications range (minimum flyby periapsis radius) between the probe and the spacecraft. This aim point has a periapsis radius of $2.25R_S$ and a θ_{aim} that varies between −17.4° to −19.1° from the start to the end of the launch window.

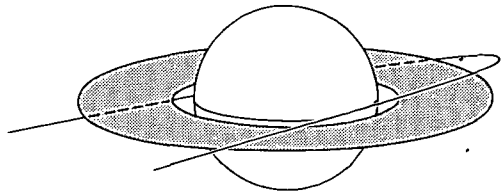

Figure 5.– Saturn passage as seen from Earth.

Consideration of post-Saturn encounter objectives for the flyby spacecraft after the probe mission is completed leads to an alternative aim point specification for the 1979 Saturn direct mission. It would be highly desirable to pass Saturn in such a way as to send the spacecraft on to Uranus after completion of the probe mission if such a passage would not overly compromise the Saturn objectives. The required passage conditions at Saturn and the arrival date at Uranus for a Saturn swingby to Uranus are shown in figure 6 as a function of Saturn arrival date for the 1979 launch opportunity. On the left, the required periapsis radius at Saturn in shown and, for the chosen Saturn arrival date of 2445433 (required to achieve a Titan encounter), a periapsis radius of $2.2R_S$ and a θ_{aim} of about −30.5° is required to continue to Uranus. The subsequent arrival date at Uranus (shown on the right) is September 13, 1987. The total trip time to Uranus is thus almost 8 years.

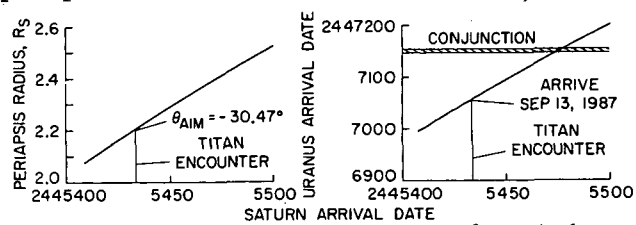

Figure 6.– Saturn passage requirements for swingby to Uranus (1979).

This aim point is indicated by the labeled circle on the aiming diagram of figure 7. The previously discussed equatorial occultation aim point is also shown for comparison. The aim point of post-encounter swingby to Uranus lies just outside the ring avoidance contour and is also near the diametric occultation condition. A probe deposited from this aim point would enter at about 30° north latitude. The communications range from the probe to the spacecraft would be nearly the same as for the equatorial occultation aim point. The spacecraft would enter body occultation at about 10° north latitude and exit at 45° south latitude. Thus, allowing for a post-encounter trajectory to Uranus requires the probe to enter farther away from the equatorial zone of Saturn and somewhat compromises the occultation measurements. However, until the science objectives of the mission have been examined in greater detail, it seems reasonable to consider both aim points as possible alternatives.

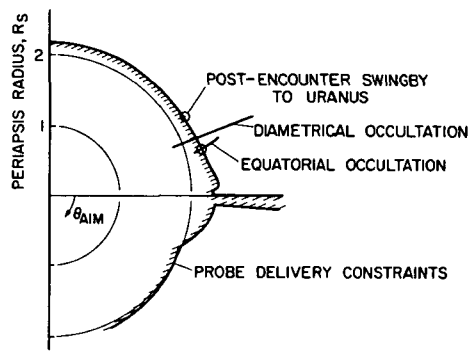

Figure 7.– Alternative aim points at Saturn (1979).

Entry conditions– Having arrived at a specification for possible aim points at Saturn for the 1979 launch opportunity, it is now possible to examine the resulting entry conditions of a probe deposited from the flyby trajectories. The two entry parameters of importance to the probe design are entry angle and entry angle of attack of the probe relative to the rotating atmosphere.

Since the spinning Pioneer spacecraft is to be used as the probe carrier, the probe will be mounted with its axis of symmetry coincident with the spin axis of the spacecraft. The probe will be targeted for entry with one of two possible deflection modes. The first is called the deflected probe mode in which the spacecraft and probe are initially targeted at the appropriate flyby periapsis radius and, at some point inside the sphere of influence of the planet, the probe is separated from the spacecraft and deflected toward the planet by an impulsive rocket. The second is called the deflected spacecraft mode in which the spacecraft and probe are initially targeted at the appropriate entry location and, at some point inside the sphere of influence of the planet, the probe is separated and the spacecraft is deflected to the appropriate nonimpacting trajectory. Both modes have system and operational advantages and disadvantages, as will be discussed later.

The Pioneer spacecraft spins with its axis of rotation always pointing toward Earth so that communications are continuously available. Since it is operationally desirable not to lose that communications link, separation and deflection must be accomplished in an Earth-oriented manner. In addition, it is highly desirable that the probe be as simple as possible; therefore, the probe will be spin-stabilized without any capability to perform attitude changes. This further constrains the attitude of the probe to be Earth-oriented for both deflection modes and, in general, results in a non-zero angle of attack at entry.

With this attitude constraint, if either the spacecraft or the probe is separated or deflected at large distances (say greater than $300R_S$) from the planet, but still within the sphere of influence, the difference between the entry conditions for the two modes is negligible and is not a function of separation radius. Thus, the resulting entry angle of attack as a function of inertial entry angle is shown in figure 8 for the previously discussed arrival date and conditions and for the two specified aim points. The shaded bands indicate the small change in the variation across the launch window in 1979. Basically, the angle of attack decreases to a minimum near an entry angle of about −50° and then increases for higher entry angles for both aim points. To minimize undesirable dynamic oscillations of the probe during entry, it is desirable that the initial angle of attack be less than about 20°; thus, inertial entry angles of about −20° to −80° meet this requirement.

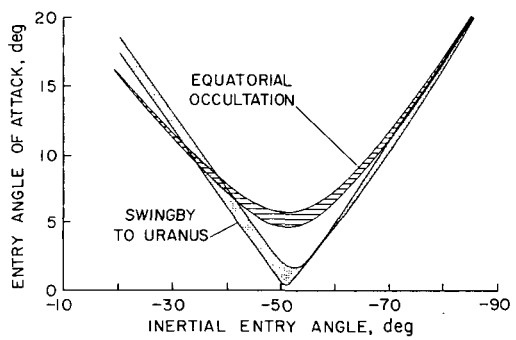

Figure 8.– Entry angle of attack at Saturn (1979).

Another entry condition of possible interest is the solar elevation angle at the entry point. Some of the possible probe experiments may desire a daylight entry condition and, in fact, daylight throughout the descent into the atmosphere. The solar elevation angle at the entry point is shown in figure 9 as a function of inertial entry angle for the two aim points considered. Entries steeper than −15° have daylight conditions at entry. The secondary scale shows the amount of time after entry before the Sun sets on the descending probe. Since the descent to 10 bars will take about 1 hour, only entries steeper than −35° can provide daylight during the entire descent.

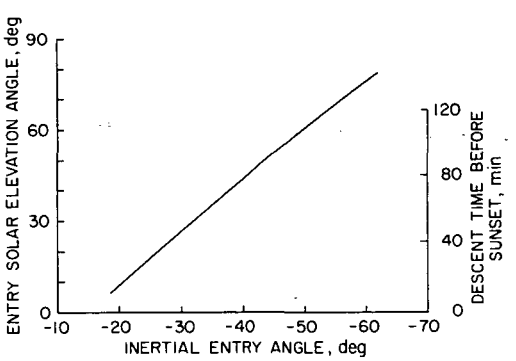

Figure 9.– Solar elevation at entry at Saturn (1979).

Since the deceleration encountered by the probe during entry increases rapidly as entry angle becomes steeper, it is obvious that a compromise must be reached to choose the entry angle for the probe. In fact, since the deflection and phasing velocity requirements and the relative communications geometry between the probe and spacecraft are strong functions of entry angle, such a choice cannot be made until those two factors are discussed.

Deflection/phasing velocity requirements– As stated before, each deflection mode (i.e., deflected probe or deflected spacecraft) has advantages and disadvantages. The principal advantage for the deflected probe mode is that most planetary quarantine considerations for the spacecraft are eliminated. However, since the deflection maneuver must be performed along the Earth line (spin axis of the probe), the maneuver is highly inefficient and results in an increase in the speed of the probe which must, in turn, be compensated for by spacecraft maneuvers to maintain a good communications geometry.

The principal advantage to the deflected spacecraft mode is the elimination of any major propulsion requirement for the probe. In addition, the spacecraft can easily be equipped with both axial and radial thrusters so that maneuvers can be made in both the Earth-line (axial) and perpendicular directions. This results in an efficient maneuver capability. The problem of planetary quarantine still remains. However, since there will probably be two separate propulsion systems (one for attitude and spin-rate control and one for major maneuvers), the resulting redundancy may be sufficient to satisfy quarantine probabilities. This problem will require much more extensive study, but for this report only the deflected spacecraft mode will be considered further.

With all the constraints discussed previously, the spacecraft deflection maneuver consists of two separate maneuvers – one along the Earth line (axial) and one perpendicular to that line – to deflect the spacecraft from its impacting entry trajectory to the desired aim point so as to avoid the rings and accomplish other scientific desires. At the same time, the maneuver must appropriately phase the spacecraft and the lead time of the probe so that the spacecraft will be nearly above the probe when it reaches a pressure of 10 bars. This minimizes the communications distance when the atmospheric attenuation to the RF signals is the worst. The parametric variation of these two velocity maneuvers to accomplish these goals is shown as a function of separation radius and inertial entry angle in figure 10. On the left, the variation of maneuver velocity with separation radius is shown for an inertial entry angle of −30° and, on the right, the variation of maneuver velocity is shown with inertial entry angle for a separation radius of $500R_S$. These results are for the equatorial occultation aim point. Since the required periapsis radius for the post-encounter swingby to Uranus is slightly less than that for the equatorial occultation condition, the deflection velocity requirements for that aim point will be just slightly less than the results shown in figure 10.

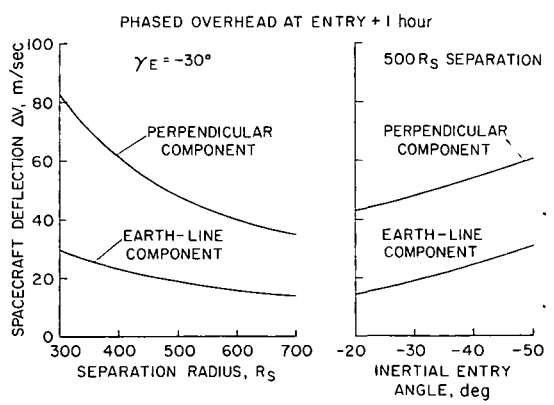

Figure 10.– Deflection/Phasing ΔV at Saturn (1979).

As expected, the maneuver velocity requirements decrease with increasing separation radius and increase as entry angles become steeper. Since the effect of guidance uncertainties on the entry dispersions of the probe increases as separation radius increases, and since the total velocity requirement does not appreciably decrease

beyond a separation radius of $500R_S$, a separation radius of $500R_S$ was chosen as a reasonable compromise. On the right in figure 10, for this separation radius, the total maneuver requirement varies between 60 to 90 m/sec for entry angles between −20° to −50°.

The results in figure 10 are for a descent time of 1 hour. If it were desired to either increase or decrease the lead time of the probe, this could be done with practically no penalty. The reason for this is shown in figure 11. The spacecraft velocity vectors before and after deflection at a separation radius of $500R_S$ are shown relative to the Earth line. To deflect from a −30° entry trajectory to the flyby aim point and to phase the spacecraft above the probe at entry time plus 1 hour, the spacecraft is required to perform an Earth-line (axial) maneuver of 19 m/sec toward Earth followed by a 48-m/sec maneuver in-plane with the trajectory and perpendicular to the Earth line. The resulting spacecraft velocity vector is about 50° to the Earth line. If the probe lead time is to be decreased, the length of the spacecraft velocity vector after deflection should be increased. This could have been accomplished during the deflection maneuver by increasing the perpendicular component and by decreasing the axial component. Since the angle with Earth line is nearly 45°, a nearly exact compensation between the change in the two components results in keeping the total velocity requirement the same.

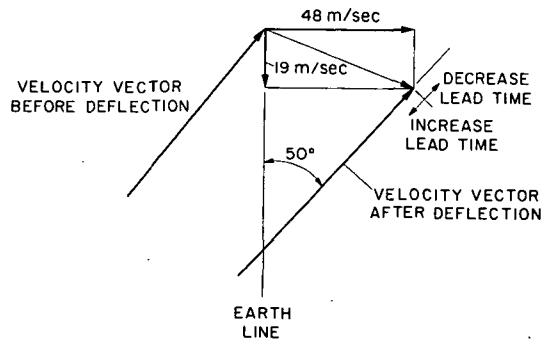

Figure 11.– Deflection/phasing compensation.

Communication geometry– The resulting geometric variations between the probe and spacecraft from entry through descent are shown in figure 12. On the left, the communications range at entry and at entry plus 1 hour is shown as a function of inertial entry angle. Communications range increases as entry angle becomes steeper. The other geometric parameter of primary importance is the aspect angle that the probe is seen from the flyby spacecraft. This angle is measured from the spacecraft spin axis (Earth-oriented) in the direction opposite the Earth to the position of the probe. This angle is a measure of the difficulty of receiving the probe signals at the spacecraft. Since the Pioneer spacecraft has its large high-gain antenna pointed at Earth, it is physically difficult to receive signals from aspect angles much greater than about 90°. The maximum value of this aspect angle which occurs at the end of the probe descent (10 bars) is shown on the right side of figure 12 as a function of inertial entry angle. Entry angles steeper than −30° are desired to keep this angle below 90°.

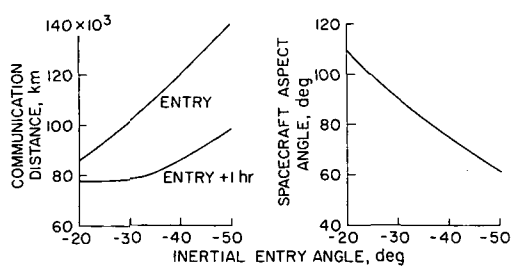

Figure 12.– Communications geometry at Saturn (1979).

Considering the conflicting desires to keep the entry angle of attack low, to possibly maintain daylight during the descent, to keep the deflection velocity requirements small, to keep the entry deceleration down, to shorten the communications range, and finally to maintain a reasonable receiving aspect angle from the probe to the spacecraft, it appears that an inertial entry angle of about −30° is desirable. With an entry angle of −30°, the variation of four key communications parameters with time from before entry through the 1 hour descent is shown in figure 13. These

parameters are spacecraft aspect angle, probe aspect angle (the angle that the spacecraft is seen from the probe measured from its axis of symmetry in the direction of the base of the probe to the position of the spacecraft), the range rate between the probe and spacecraft (a measure of the doppler shift that must be tracked by the spacecraft), and finally the range between the probe and spacecraft.

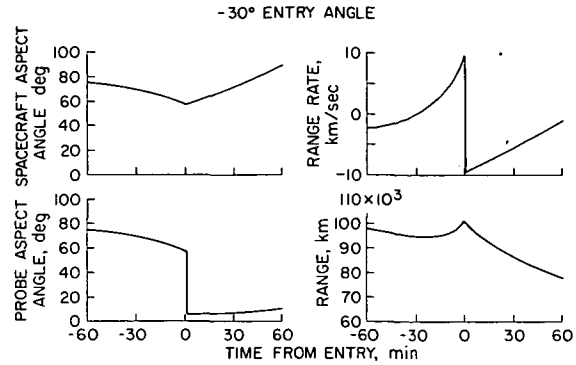

Figure 13.– Communications parameters at Saturn (1979).

The spacecraft aspect angle varies between 60° to 90° from entry to the end of descent, while during the same time the probe aspect angle varies from 5° to 10°. An undirected antenna with a beamwidth of 30° can be used on the spacecraft and a narrow-beam (10°) centerline antenna can be used on the probe. The range rate between the probe and spacecraft indicates a ±10-km/sec variation that results in a ±30-kHz variation in frequency which must be tracked by the spacecraft receiver for an L-band (1000-MHz) relay link. The range variation between the probe and spacecraft indicates a maximum range of 100,000 km at entry, decreasing to about 80,000 km at the end of the descent. This represents a 2-dB increase in gain during descent, which will probably be compensated for by a like increase in atmospheric attenuation.

1980 Saturn/Uranus Missions

Selection of heliocentric trajectory– The second and third launches in the mission set are to be launched during the 1980 opportunity to Saturn with a possible swingby to Uranus. The launch window for the range of spacecraft weights of interest for the 1980 Saturn/Uranus mission is shown in figure 14. The arrival date at Uranus is shown as a function of launch date at Earth for several spacecraft weights. Again, dates are indicated in both the Julian and Gregorian calendars. For this opportunity for the range of dates of interest, the Earth-departure declinations are well below 33° and thus the launch azimuth constraint does not penalize the mission. Trips to Uranus arriving within a few days of Julian dates 2446780 and 2447150 are excluded (as shown by the shaded band) because Earth and Uranus are at conjunction at that time, resulting in a loss of communications with the spacecraft. Similarly, arrivals at Uranus near 2446960 are also excluded because at the time of Saturn flyby on the way to Uranus, Earth and Saturn are at conjunction. Finally, arrivals at Uranus before 2446950 are excluded since such trajectories result in required close passages of Saturn and a passage of the spacecraft through the visible ring structure.

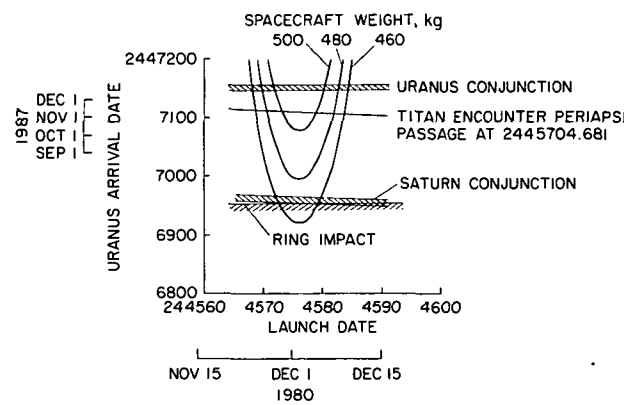

Figure 14.– 1980 Saturn/Uranus launch window.

As shown in the figure, the launch window available for a 480-kg spacecraft is not overly large. A 2-week launch period can be obtained for trip times of about 7.4 years (i.e., arriving at about

2447250). However, a 2-week launch period is too marginal considering two launches are to be made from the same pad during the launch window. About 10 days are required to recycle a launch pad after the first launch; thus, if the first launch were delayed a day or two, only a day or two after the pad recycle period would remain to complete the second launch. In addition, if the spacecraft weight were to increase, the launch period would be smaller. Therefore, it seems marginal to expect two launches from a single pad in 1980 on Saturn/Uranus trajectories. Fortunately, the Saturn/Uranus launch window can be augmented by considering the possibility of launching the second mission on a Jupiter/Uranus swingby trajectory.

The launch window for the 1980 Jupiter/Uranus mission is shown in figure 15 for a 480-kg spacecraft. Superimposed on this window is the corresponding launch window for the Saturn/Uranus mission. Using Jupiter/Uranus trajectories increases the available launch window to Uranus after the Saturn/Uranus window by about two weeks. Therefore, the following launch strategy has been devised for the 1980 opportunity. The first launch is targeted onto a Saturn/Uranus trajectory arriving at Uranus near 2447110 (passes Saturn near 2445700). A 12-day launch window is available for this opportunity. If the first launch is made within the first day, the pad may be recycled (10 days) and, if possible, a second Saturn/Uranus launch can be made. If this cannot be done during the next day, then a Jupiter/Uranus launch is made. To provide for a 7-day launch window for the first launch and a 10-day pad recycle period and a 7-day launch period for the second launch (i.e., a total window of 24 days), an earliest arrival date at Uranus of 2446523 was chosen for the Jupiter/Uranus trajectory. An additional trajectory arriving at Uranus at 2447100 was also chosen to study the effects of arrival date at Uranus for this mission. This trajectory provides an additional 18-day launch window over the 12-day window for the Saturn/Uranus trajectory.

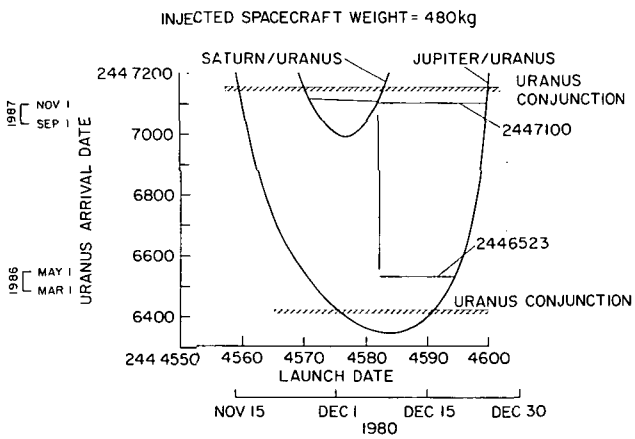

Figure 15.– 1980 Jupiter/Uranus launch window.

Since it may be desirable to have an additional Titan encounter on the 1980 Saturn/Uranus trajectory, a search was made for such encounters near the chosen passage date. Such an encounter occurs for a periapsis passage date at Saturn of 2445704.681. The encounter with Titan is shown in figure 16. Again, the distance from Titan is shown as a function of solar phase angle as seen from the spacecraft. The encounter is not nearly as good as that for the 1979 opportunity. The closest approach distance is about 320,000 km because of the higher arrival declination for the 1980 opportunity. The encounter may be of doubtful value, but it does not seem to penalize the probe mission in any way, so the Saturn/Uranus launch window has been defined to pass Saturn at the fixed appropriate date. The total launch window for 1980 is indicated by the labeled lines in figure 15.

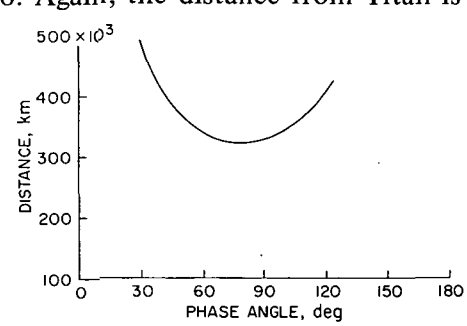

Figure 16.– Titan encounter (Saturn periapsis at 2445704.681).

Aiming conditions (1980 Saturn/Uranus at Saturn)– Having chosen the heliocentric trajectory and hence specified the arrival conditions, it is now possible to specify the aiming conditions for the encounter with Saturn and Uranus for each possibility. First, the options exist at Saturn on the Saturn/Uranus trajectory to either deposit the probe at Saturn and optimize the science at Saturn (e.g., conduct an equatorial occultation passage), or deposit the probe at Saturn and fly the spacecraft on to Uranus, or fly the spacecraft and probe on to Uranus.

The specification of the aim point for each option is very similar to the specification for the 1979 opportunity (see fig. 4). The aiming diagram is shown in figure 17. Again, the right-hand side of the impact plane is shown and the various ring avoidance contours are indicated. The equatorial occultation aim point is indicated (labeled circle) as is the required passage conditions for a swingby to Uranus. The equatorial occultation aim point has a periapsis radius of $2.30R_S$ and $\theta_{aim} = -20.0°$. The swingby to Uranus requires a periapsis radius of $2.73R_S$ and $\theta_{aim} = -28.7°$. A comparison of these results with the conditions for the 1979 opportunity indicates very similar values except for the periapsis radius to swingby to Uranus, which is somewhat higher. Therefore, the entry conditions, deflection/phasing velocity requirements, and communications geometry for the equatorial occultation aim point for the 1980 opportunity are very similar to that defined previously for the 1979 opportunity and will not be considered further in this report. Some additional discussion is required, however, of the deflection and communication requirements for depositing a probe at Saturn from the aim point conditions to swingby to Uranus.

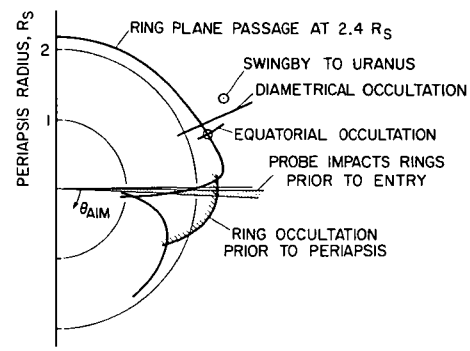

Figure 17.– Aiming diagram at Saturn (1980).

Deflection/phasing velocity requirements (1980 Saturn/Uranus at Saturn)– Again, only the spacecraft deflection mode is to be considered. The increased periapsis radius requirements to swing by Saturn to Uranus for the 1980 opportunity requires, of course, a greater deflection impulse than the 1979 case to deposit a probe at Saturn from that aim point if the probe is separated at the same distance from Saturn. The spacecraft deflection velocity required to deflect from an impacting −30° entry trajectory to the $2.73R_S$ periapsis condition and to phase the spacecraft nearly overhead of the probe when it reaches 10 bars is shown as a function of separation radius in figure 18. Again, the variation of the Earth line and perpendicular components are shown. It can easily be seen that to keep the total deflection requirement to about 70 m/sec (the same as for the 1979 opportunity), the probe must be separated at about $700R_S$ instead of $500R_S$, as in the 1979 case. This change should not materially affect the guidance dispersions.

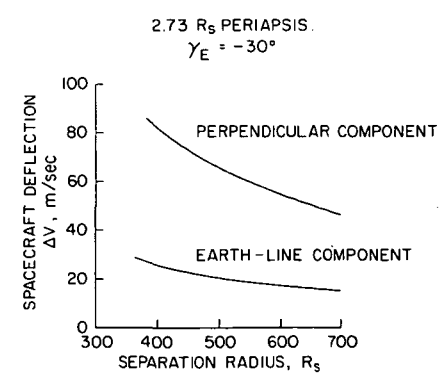

Figure 18.– Deflection/phasing ΔV at Saturn (1980).

Communication geometry (1980 Saturn/Uranus at Saturn)– The resulting geometric variations between the probe and spacecraft for depositing a probe at Saturn from a Saturn/Uranus trajectory are shown in figure 19. As

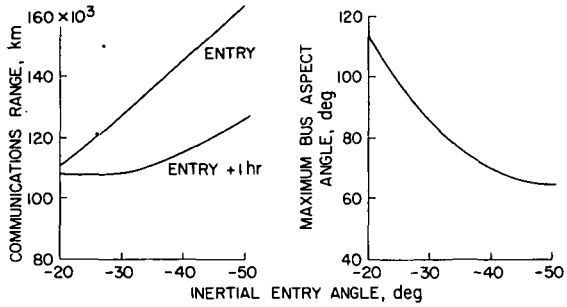

Figure 19.– Communications geometry at Saturn (1980).

shown on the left, the major effect of the higher periapsis requirement over the 1979 case is, of course, to increase the communications range for various entry angles. For a −30° inertial entry angle, the range at entry is about 125,000 km as compared with 100,000 km for the 1979 mission. On the right-hand side of the figure, it can be seen that the maximum spacecraft aspect angle is very similar to that for the 1979 mission and is less than 90° for entry angles steeper than −30°. The increase in range means that if this option is to be used, the communication system must be designed with a margin 2 dB greater than that required for the lower periapsis radius. This does not seem to be significant.

Aiming conditions (1980 Saturn/Uranus at Uranus)– If the option is exercised to pass Saturn and carry the probe on to Uranus, then the arrival at Uranus will be about 2447110 (near November 1, 1987). The specification and the constraints on the aim point at Uranus are shown in the aiming diagram of figure 20. The plane of the diagram is again the impact plane perpendicular to the hyperbolic approach vector at Uranus. The polar coordinate, θ_{aim}, is again the azimuth of the flyby trajectory measured clockwise from a vector in the impact plane which is the intersection of the impact plane and the equatorial plane. Since the pole of Uranus lies nearly in the plane of the ecliptic, the direction of ecliptic north is to the right in figure 20 (indicated by the labeled arrow). The projection of the planet, the north pole, the equator, and the sub-Earth and subsolar points are indicated on this plane.

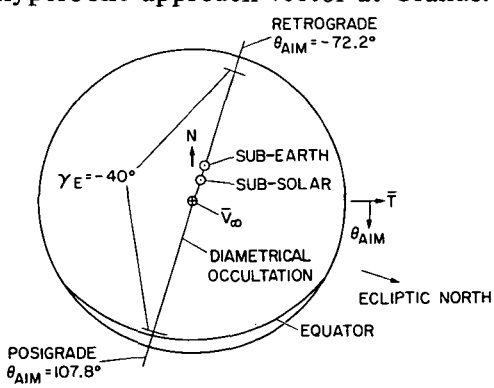

Figure 20.– Aiming diagram at Uranus (1980 Saturn/Uranus).

As with Saturn, one of the most important measurements to be accomplished is a dual-frequency RF occultation of the atmosphere of Uranus. Again, it would be desirable to make such a measurement at nearly the same latitude as that of the probe entry and to make the occultation nearly diametrical. The straight line through the approach vector, $\overline{V}_\infty$, and the sub-Earth point provides such a diametrical occultation.[2] Such conditions can be obtained on either a posigrade (relative to ecliptic north) or a retrograde flyby.

Since the approach to Uranus is nearly toward the north pole, neither flyby orientation possesses any significant advantage for reduced entry speed due to the relative motion of the rotating atmosphere. However, the entry angle of attack of an Earth-oriented probe results in the selection of a preferred flyby orientation. The resulting entry angle of attack as a function of inertial entry angle for the two flyby orientations is shown in figure 21. Obviously, the retrograde entry is preferred due to the low entry angle of attack. Acceptable angles of attack exist for a wide

[2] Because of the proximity of the $\overline{V}_\infty$ vector and the sub-Earth point, any flyby orientation provides a near-diametrical occultation. However, as will be shown, the entry angle of attack is very sensitive to the aim point specification.

range of entry angles. Again, the choice of entry angle depends on the effect of entry angle on the deflection and phasing velocity requirements and relative communications geometry between the probe and spacecraft.

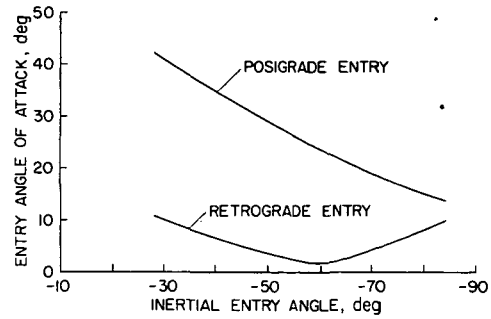

Figure 21.– Entry angle of attack at Uranus (1980 Saturn/Uranus).

Deflection/phasing velocity requirements (1980 Saturn/Uranus)– As with Saturn entry, only the spacecraft deflection mode is to be considered for Uranus. Because the approach to Uranus is nearly toward the north pole, the rotation of the atmosphere of Uranus carries the probe during terminal descent nearly perpendicular to the plane of flight of the flyby spacecraft. The descent to a pressure level of 10 bars requires about 48 min and thus the probe rotates about 16° relative to the original entry point. Therefore, to balance the position of the spacecraft over the probe during the terminal descent, the spacecraft must be deflected slightly out of plane from the original aim point for probe delivery in the direction of rotation of the atmosphere. This required change in aim point is shown in figure 22. The initial targeting of the probe and spacecraft is made to be at $\theta_{aim} = -63.9°$. After separation, the spacecraft is deflected to a higher periapsis radius and to $\theta_{aim} = -72.2°$ for diametrical occultation conditions. The probe motion (shown in this case for a −40° inertial entry angle) is balanced on either side of the flyby trajectory.

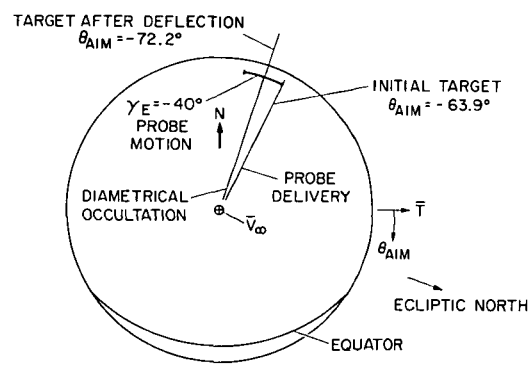

Figure 22.– Spacecraft aim point biasing at Uranus (1980 Saturn/Uranus).

It is desirable, of course, to keep the communications range between the probe and spacecraft for the Uranus entry case the same as that required for Saturn entry. Since Uranus is about half the size of Saturn, the flyby periapsis radius should be $3R_U$ (Uranus radii) or less. The total spacecraft deflection velocity requirements (to raise periapsis, to phase the spacecraft relative to the probe, and to correct for the out-of-plane motion of the probe) are shown parametrically in figure 23. The velocity requirement is shown as a function of separation radius at a fixed periapsis of $3R_U$ (on the left) and as a function of periapsis radius at a fixed separation radius of $800R_U$ (on the right). Both figures are for a −40° inertial entry angle. Again, the total deflection maneuver consists of an Earth-line component and a component perpendicular to the Earth line. To keep the total deflection velocity requirement (i.e., the sum of the two components) nearly the same as that for Saturn, the probe must be separated at a radius of about $800R_U$ from Uranus.

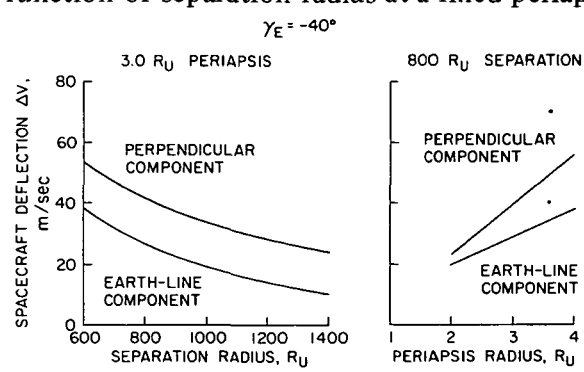

Figure 23.– Deflection/phasing ΔV at Uranus (1980 Saturn/Uranus).

Communications geometry (1980 Saturn/Uranus at Uranus)– The final choice of periapsis radius and entry angle is strongly dictated by the communications geometry between the probe and spacecraft. The geometry parameters of importance are the communication range at entry and during descent and the maximum antenna aspect angles at the spacecraft and the probe. The variation of these parameters is shown parametrically with respect to periapsis radius and entry angle in figures 24 and 25. In figure 24, the communications range and antenna aspect angles are shown as a function of periapsis radius for a fixed entry angle of −40°. In figure 25, the same

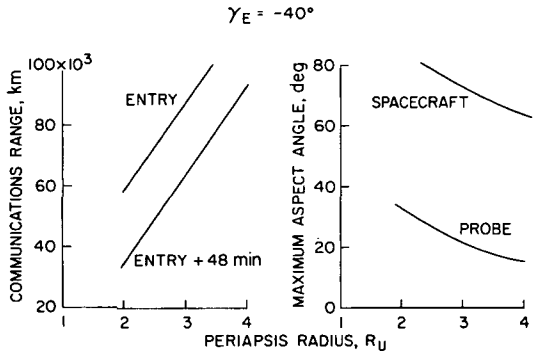

Figure 24.– Communications geometry at Uranus (1980 Saturn/Uranus): effect of periapsis radius.

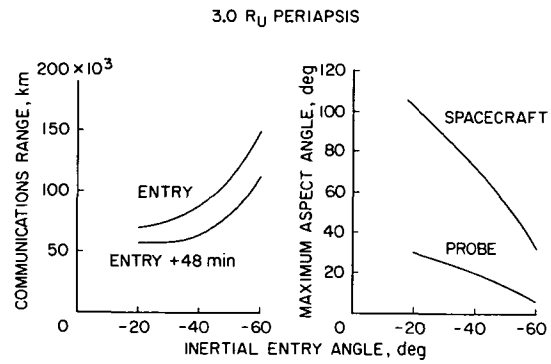

Figure 25.– Communications geometry at Uranus (1980 Saturn/Uranus): effect of probe entry angle.

parameters are shown as a function of inertial entry angle for a fixed periapsis radius of $3R_U$. From the results shown in these figures, it can be seen that, conveniently, the communications range can be made 90,000 km at entry and 65,000 km at the end of descent (nearly the same as at Saturn) while a spacecraft aspect angle less than 70° and a probe aspect angle less than 20° are maintained if a periapsis radius of $3R_U$ and an inertial entry angle of −40° are chosen. The figures indicate that periapsis radii less than the chosen value result particularly in higher probe aspect angles, and that entry angles steeper than −40° result in a markedly increased communications range.

For the chosen flyby and entry conditions, figure 26 indicates the variation of the four key communications parameters with time from before entry through the 48-min descent to 10 bars. The spacecraft aspect angle varies between 40° to 70° from entry to the end of descent, while during the same time the probe aspect angle varies from 15° to 5°. Thus an undirected antenna with a beamwidth of 30° can be used on the spacecraft. This is the same as for Saturn entry, but the position of that antenna with respect to the spacecraft axis must be different than for Saturn. The required centerline antenna beam angle of 15° for the probe is somewhat larger than that required at Saturn. The variation in range rate between the probe and spacecraft – from +10 to −15 km/sec – is slightly higher than at Saturn. Finally, the communications range varies between 88,000 km at entry to about 65,000 km at the end of the descent.

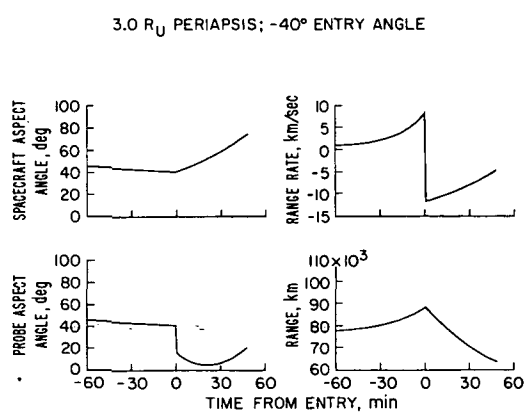

Figure 26.– Communications parameters at Uranus (1980 Saturn/Uranus).

1980 Jupiter/Uranus

If it is not possible to launch the second probe mission in 1980 on a Saturn swingby to Uranus, the second mission that year can be launched on a Jupiter swingby to Uranus. To provide an appropriate launch window and to examine the effects of arrival date at Uranus on the probe mission, arrival dates at Uranus of 2446523 (April 3, 1986) and 2447100 (November 1, 1987) were chosen (see fig. 15). The passage dates at Jupiter are approximately 2445055 (March 26, 1982) and 2445110 (May 20, 1982), respectively. The appropriate swingby periapsis radii at Jupiter are about $15R_J$ (Jupiter radii) and $26R_J$, respectively, well outside any radiation danger from the intensive radiation belts at Jupiter.

Aiming conditions (1980 Jupiter/Uranus at Uranus)– As for the 1980 Saturn/Uranus mission, the aiming conditions at Uranus are arbitrarily chosen to provide a diametrical occultation with respect to Earth. There are two aim points for each arrival date which provide such an occultation as listed:

Arrival date	θ_{aim}
2446523	23.5°, −156.5°
2447100	27.0°, −153.0°

The resulting entry angle of attack for the two diametrical occultation flyby orientations for each arrival date is shown in figure 27 as a function of inertial entry angle. Again, in both cases, the entry corresponding to the negative θ_{aim} is preferred because of the low entry angle of attack for an Earth-line-oriented probe. The later arrival date results in slightly higher entry angles of attack.

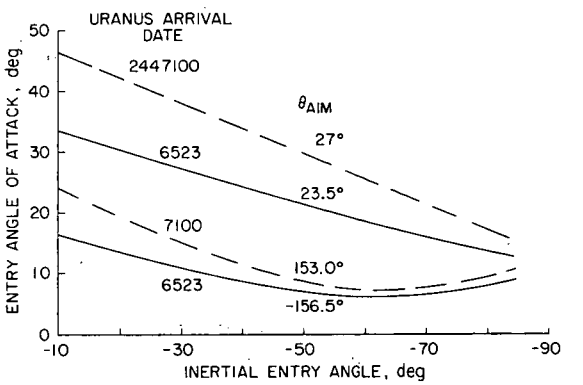

Figure 27.– Entry angle of attack at Uranus (1980 Jupiter/Uranus).

Deflection/phasing velocity requirements (1980 Jupiter/Uranus at Uranus)– Again, to balance the position of the spacecraft over the probe during its descent to 10 bars, the spacecraft must be deflected slightly out of plane in the direction of the rotation of the atmosphere. The initial targeting is thus made to be at a θ_{aim} as indicated:

Aim Points
1980 Jupiter/Uranus at Uranus

Arrival date	Initial θ_{aim}	Final θ_{aim}
2446523	−145.2°	−156.5°
2447100	−137.3°	−153.0°

The spacecraft deflection velocity requirements are shown parametrically in figure 28. The two velocity components are shown (on the left) as a function of separation radius at a fixed periapsis radius of $3R_U$ and as a function of periapsis radius at a fixed separation radius of $800R_U$ (on the

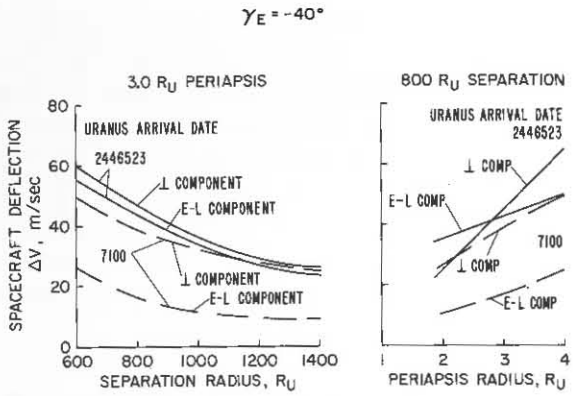

Figure 28.– Deflection/phasing ΔV at Uranus (1980 Jupiter/Uranus).

right). Both are for a −40° inertial entry angle. The fast trip to Uranus, arriving at 2446523, has a considerably higher total deflection velocity requirement. The slower trip has deflection velocity requirements much lower and are nearly the same as that for the Saturn/Uranus trajectory. Thus, if a common system is to be used for both the Saturn/Uranus and Jupiter/Uranus mission opportunities, it appears that the shorter trip times available with the Jupiter/Uranus trajectories cannot be used without a high deflection velocity penalty or without increasing the separation location to beyond $1000R_U$.

Communications geometry (1980 Jupiter/Uranus at Uranus– Again, the final choice of periapsis radius and entry angle is dictated by the communications geometry between the probe and spacecraft. The parametric variation of the communications range and aspect angles with respect to periapsis radius and entry angle are shown in figures 29 and 30. These results for both Uranus arrival

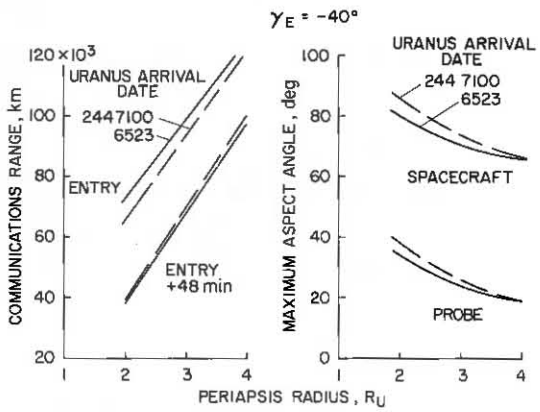

Figure 29.– Communications geometry at Uranus (1980 Jupiter/Uranus): effect of periapsis radius.

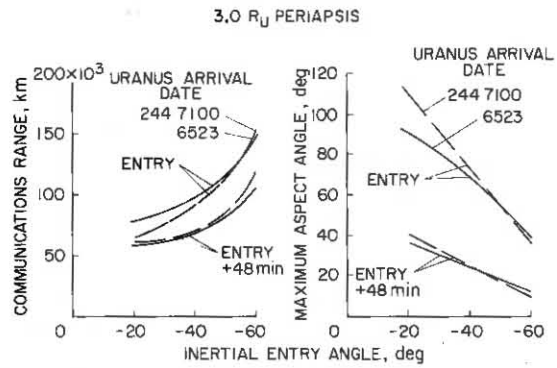

Figure 30.– Communications geometry at Uranus (1980 Jupiter/Uranus): effect of Probe entry angle.

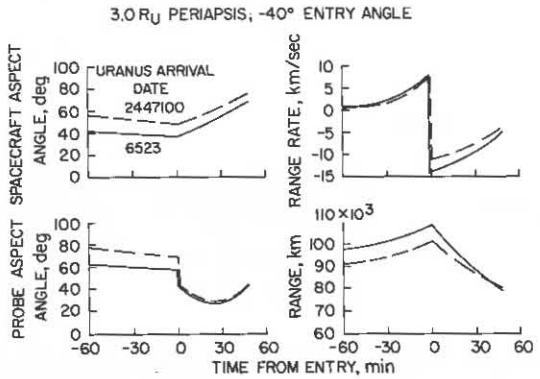

Figure 31.– Communications parameters at Uranus (1980 Jupiter/Uranus).

dates are very similar to the previous results for the Saturn/Uranus mission. Thus, a flyby periapsis radius near $3R_U$ and an entry angle of about −40° appear appropriate.

The variation of the four key communications parameters with time for the above conditions is shown in figure 31. Again, the variations are very similar to those for the 1980 Saturn/Uranus mission and for the 1979 Saturn direct mission, indicating that a common probe-spacecraft system can be designed for all three missions.

CONCLUSIONS

The series of recommended outer-planet atmospheric probe missions to Saturn and Uranus has been examined in detail. The mission feasibility and the programmatic options available have been explored. Desirable targeting options that maximize the scientific return from the missions have been determined.

It is recommended that the following launch and program strategy options be considered to maximize scientific return from the series of missions and to alleviate the short launch window available in 1980. In late 1979, a single launch can be made directly to Saturn, depositing the probe into Saturn's atmosphere in early 1983. Emphasis can be placed on Saturn flyby science or, at some compromise, the spacecraft can be placed onto a post-Saturn trajectory to fly by Uranus, arriving in late 1987. In late 1980, two launches can be made: the first on a trajectory to Saturn and the second on a trajectory to Jupiter. About 1 year out from Saturn a decision can be made, depending on the success or failure of the 1979 mission to commit the second probe to Saturn or to fly by Saturn to Uranus. If it is decided to commit the probe to Saturn, entry occurs in early 1984 and it is again possible to either emphasize Saturn flyby science or, at some compromise, place the spacecraft onto a post-Saturn trajectory to fly by Uranus, arriving in late 1987. If the probe is committed to Uranus, desirable flyby science can be accomplished during the pass at Saturn and probe entry at Uranus occurs in late 1987. The second mission launched in late 1980 passes Jupiter in mid-1982 at about $26R_J$ (Jupiter radii) and arrives at Uranus in late 1987. The probe is, of course, dedicated to Uranus.

It has been determined that nearly common spacecraft requirements are improsed by these missions. Spacecraft deflection velocity requirements of about 70 m/sec are required at all objectives to deliver the probe to entry. A maximum communications range between the probe and spacecraft of about 100,000 km and nearly common communications angles result for all missions. Thus, it seems apparent that a single spacecraft and probe design can be used for the entire set of missions.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, May 24, 1973

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