Paul A. Penzo

IMPACT OF SATURN'S RINGS ON MISSION ANALYSIS FOR MJS 77

Figure 1, which is drawn to scale, shows a heliocentric plot of three possible MJS 77 trajectories as seen from the ecliptic North Pole. This figure is presented to explain the spacecraft approach direction to Saturn. Although a single launch date is shown, there is a 32-day period from August 17 to September 17, 1977, during which the two Mariners can be launched. Varying the launch date will not significantly change figure 1. All trajectories currently acceptable to MJS 77 lie between the extreme trajectories shown, essentially in the ecliptic plane, with Jupiter arrival dates between February 21 and July 24, 1979, and Saturn arrival dates between October 28, 1980, and September 21, 1981. Thus, the possible arrival dates at Saturn span almost a year.

During this time the view from Earth shows the rings tilted downward from 5° to 10°. Also, at large distances the approach of the spacecraft to Saturn for the range of arrival dates is essentially from the direction of the Sun, and this direction remains fairly constant. Thus, the spacecraft, on approach to Saturn, will see the planet and rings fully lit with the rings tilted down about 10°. The characteristics of the near encounter of the Saturn flyby—that is, altitude and latitude passage at closest approach—depend upon mission constraints and scientific objectives. Thus, it is possible to pass over or under or to the left or right of the rings. Analyses are currently in progress to relate these flyby characteristics to specific science objectives and thus determine what specific trajectories should be flown. It should be noted, however, that it will be possible to alter the Saturn flyby to some extent, such as from passing close to the rings to passing further out, up to 2 or 3 months before the spacecraft arrives at Saturn. Some of the mission objectives at Saturn currently being considered—which affect the trajectory design and in particular the aim point at Saturn—are shown on the following page:

Jet Propulsion Laboratory.

Earth, Sun occultation of Saturn, rings, and satellites

Close as possible to surface

Close as possible to rings

Close encounter with Titan (~20 000 km)

Close encounter with Iapetus

Multiple satellite encounters

Post-Saturn trajectory to Uranus

Post-Saturn trajectory toward solar apex

Going over these objectives briefly, Earth and Sun occultation by Saturn is easily obtainable and does not greatly restrict the selection of the Saturn aimpoint. The best Earth occultation by the rings, however, requires a passage slightly above the ring plane, assuming direct passage of Saturn. This is somewhat incompatible with flying as close as possible to the surface and the rings,

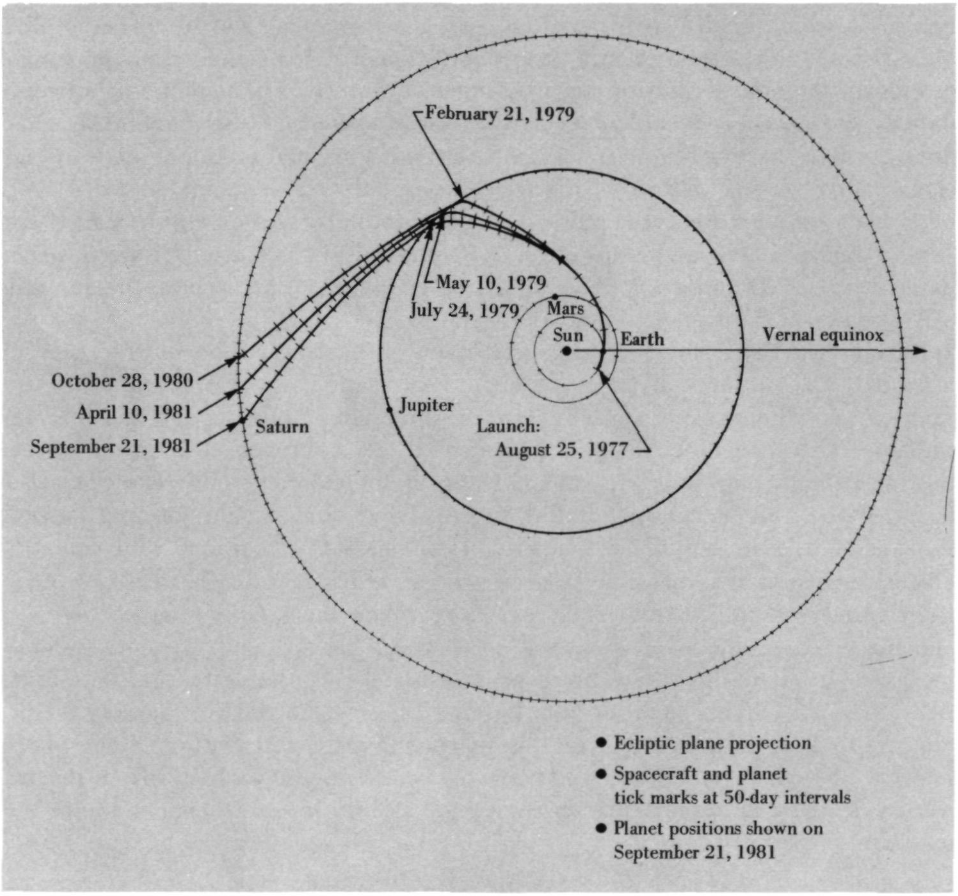

FIGURE 1.—*Heliocentric plan view of transfer trajectories.*

which is best accomplished by flying slightly below the rings. This latter requirement assumes a ring plane crossing-distance constraint (i.e., that the spacecraft must cross the ring plane no closer than some specified distance, now taken as 4 Saturn radii).

Another objective would be to pass close to Titan or Iapetus, say within 20 000 km, which would place restrictions on the Saturn aimpoint. There is some freedom here, since the encounter may take place with Titan anywhere in its orbit, within limits. If, in addition, it is desired to come close to Saturn, then the Titan encounter occurring before Saturn passage must pass far underneath the rings, whereas the Titan encounters after Saturn passage may pass closer, but still underneath the rings. The desire for multiple satellite encounters, say to get within 20 000 km of Titan and within 50 000 or 100 000 km of an inner satellite such as Dione, would further constrain the aimpoint and the Saturn arrival time. Requiring the spacecraft to continue on to Uranus after the Saturn encounter places a very strict requirement on the Saturn aimpoint. Here, it is necessary to remain in the ecliptic and fly very close to Saturn, perhaps through the visible rings. The final objective listed here is a post-Saturn trajectory aimed toward the solar apex, requiring the spacecraft to come up out of the ecliptic to an ecliptic latitude of about 25° to 50° and a longitude of 270°.

Relative to these objectives, the general regions of the aimpoints are shown in figure 2. The dashed line represents the ring plane, and the location of each region is about equal to the distance of closest approach to Saturn. The number

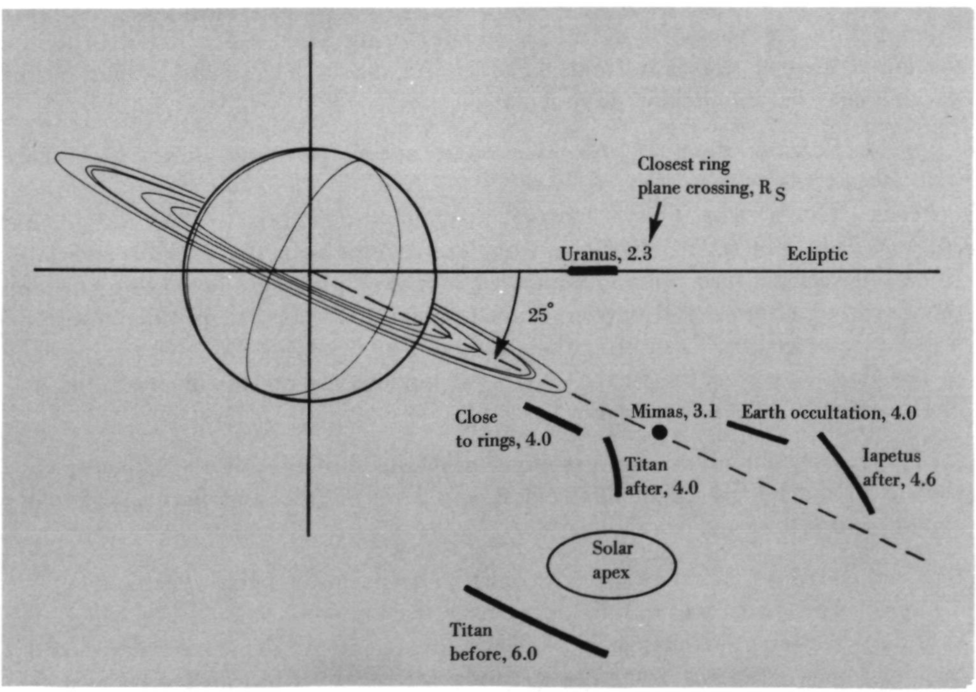

FIGURE 2.—*Mission objectives at Saturn and relation to rings.*

shown next to the stated objective is the closest ring plane crossing distance. For example, if we wish to come close to the rings, we have to aim the trajectory underneath the ring plane. This would be the ideal way of getting close to the rings and remaining outside the 4.0 R_S distance at ring plane crossing. If we wished to continue on to Uranus, we would have to pass Saturn well above the rings and remain essentially in the ecliptic. It is necessary to remain in the ecliptic in order to continue on to Uranus, which is very near the ecliptic. Also, it would be necessary to violate our current 4.0 R_S ring plane crossing constraint and cross the ring plane at about 2.3 R_S, just at the edge of the visible rings. This close approach to Saturn is necessary to cause a sufficient amount of bending by Saturn in order for the trajectory to continue in the right direction to get to Uranus.

Another objective shown in this figure is Earth occultation. This means that, as viewed from the Earth, we wish to have the spacecraft pass behind Saturn and each ring in the ring system. Data about the rings may then be obtained from the received radio signal. The best ring occultation results when the spacecraft passes Saturn slightly above the ring plane. It is interesting to note here that the closest approach distance to Saturn that will satisfy the 4.0 R_S ring plane crossing constraint is further out from Saturn than when passing underneath the rings. This is a general property of the Saturn flyby trajectories—that you can get closer to Saturn by flying under the rings than flying over them.

The "Titan after" label simply means that this is the general aim region required to obtain a close encounter with Titan after the Saturn flyby has occurred. The time of Titan encounter is about 18 hr after Saturn passage. Encountering Titan before the Saturn flyby means encountering Titan when Titan is in the portion of its orbit that is in front of Saturn. As shown in the figure, this requires passing considerably below the ring plane.

Von Eshleman Paul (Penzo), this chart seems to make things look more mutually exclusive than they really are.

Penzo That's right. This is more of a schematic diagram to show the general regions. I did not try to show the complete regions with the possible overlaps, since this can get to be very complicated. For example, there is overlap between the Earth occultation and encountering Iapetus after the Saturn encounter and also between getting Titan after the encounter and passing as close to the rings as possible. However, the further apart two regions are on this diagram, the less likely it is that an overlap exists.

Finally, the aim region for passing out in the direction of the solar apex is shown. Flying by Saturn in this region would result in a post-Saturn trajectory aimed toward the solar apex.

Robert Murphy What is the advantage of going to the solar apex?

Penzo The particles and fields people are interested in seeing where the boundary between the solar particle field ends and where the interstellar medium begins. There are measurements that they wish to take in that region to define that boundary.

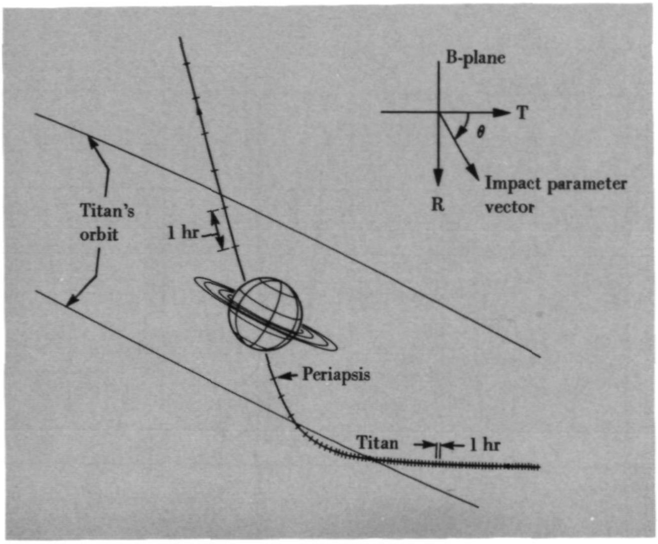

FIGURE 3.—*Sample flight path by Saturn.*

Figure 3 simply shows one trajectory satisfying a particular objective, which is to encounter Titan. In this case the trajectory begins at the lower right. The tick marks indicate fixed time intervals, so that, as you tick off each hour, the trajectory approaches Titan, then encounters Titan. Near the Titan encounter, it crosses the ring plane at 19 R_S and then continues its passage underneath the ring plane. Saturn occultation occurs just about 1 hr past periapsis, with exit from occultation occurring about 2 hr later. The second ring plane crossing, from below to above, might be at 6 or 8 R_S.

I want to point out what is called the impact parameter plane. This is simply a plane that is perpendicular to the incoming velocity vector, with Saturn at the center of the coordinate system. Neglecting Saturn's mass, the velocity vector from a very large distance is just extended along a straight line until it passes through this plane. The vector from the center of Saturn to this intersection is called the impact parameter. The T axis represents the ecliptic direction—that is, the intersection of the impact parameter plane with the ecliptic plane. The angle θ is measured from this line to the impact parameter vector in a clockwise direction and is somewhat equivalent to an inclination. That is, as you move clockwise from the T axis, you measure θ from 0° to 360° as indicated in the small sketch in figure 3.

Figure 4 shows a multiple satellite encounter analysis, with the X axis indicating the Saturn arrival date resulting in a Titan encounter at various points on its trajectory. There will be certain regions—certain locations of Titan on its orbit—where the trajectory will encounter not only Titan but also other satellites. The Titan closest approach altitude for this complete figure is 25 000 km. So in addition to Titan, you can also, for example, get close to Dione as shown. The distance of Dione will minimize at about 75 000 km when you arrive at

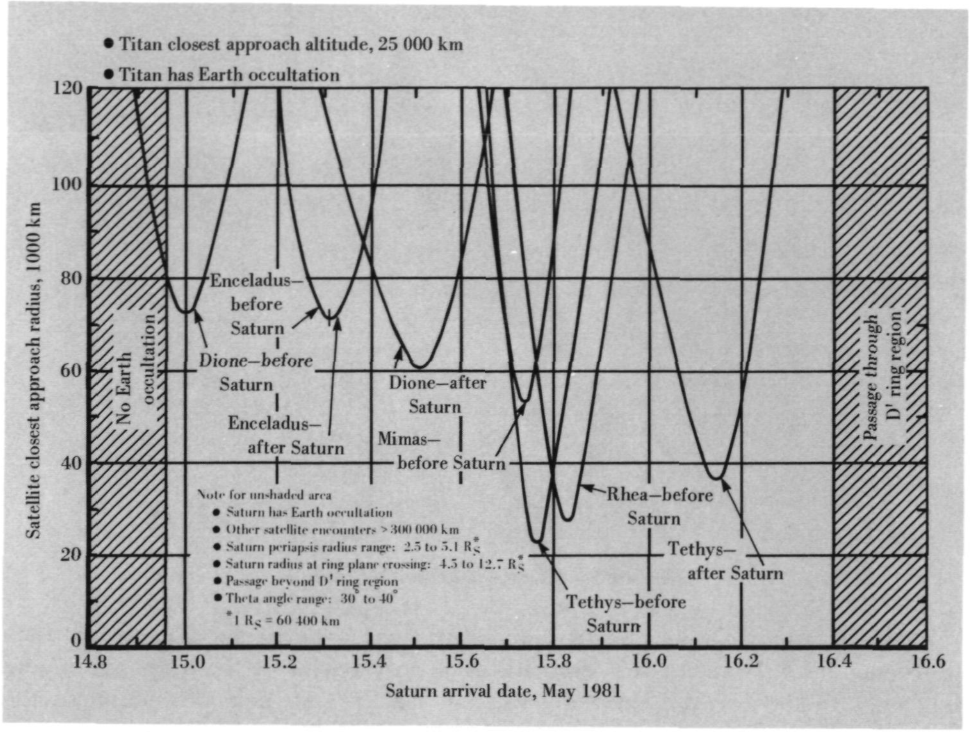

FIGURE 4.—*Saturn satellite encounter opportunities.*

Saturn on May 15, 1981. Here, you will encounter Dione before the closest approach to Saturn. As you change the date of arrival at Saturn and maintain the Titan encounter, other satellites come into the picture, and some of them bunch up at certain arrival dates. For example, on May 15.8 you can get within 40 000 km of Tethys and Rhea and 90 000 km of Mimas. Therefore, you can actually come close to three of the inner satellites in addition to coming close to Titan. We wish also to have an Earth occultation of Saturn, and that implies you do not want to arrive at Saturn prior to about May 15. If you encounter Titan before that date, as shown in this figure, you do not get Earth occultation.

As the arrival date increases, the closest approach altitude at Saturn decreases. So that as the date gets beyond 16.4 in May, you must pass through what we call the D′ region, which extends to 4 R_S in the ring plane. You can see that the D′ ring constraint plays a definite part in selecting trajectories that encounter satellites. Figure 4 applies to a single revolution of Titan. Previous or succeeding revolutions will have different characteristics relative to the secondary satellite encounters.

Another science objective is obtaining an Earth occultation of Saturn's rings. Figure 5 is a view of Saturn as seen from the Earth. In this case the equatorial plane is horizontal, and, as seen from the Earth, the spacecraft will pass behind the planet and the rings from right to left as shown. Periapsis would be close to the right edge of the figure. The hours past periapsis are marked. Here you can get occultations of rings A, B, and C and the gap between ring C and Saturn. As I mentioned in an earlier figure, this requires approaching Saturn from above the ring plane, whereas the Titan encounter requires approaching Saturn from below the ring plane, at least for the case where you get to Titan before you arrive at Saturn.

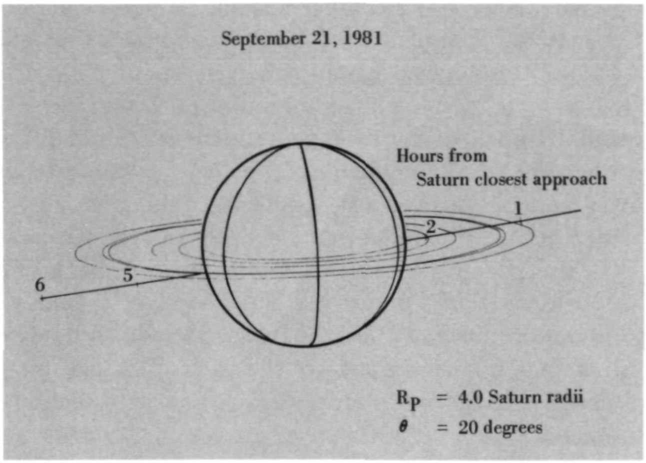

FIGURE 5.—*Saturn trajectory for good ring occultation.*

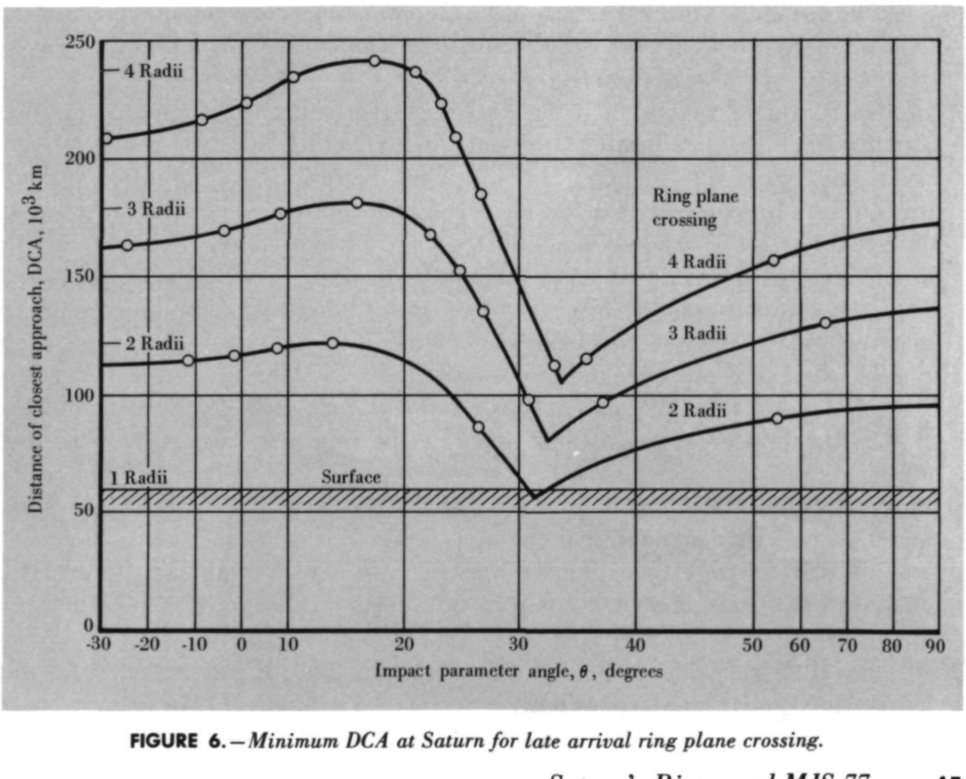

FIGURE 6.—*Minimum DCA at Saturn for late arrival ring plane crossing.*

Now, how close can you get to Saturn and still maintain a certain ring plane crossing distance? That is shown in figure 6. Ring plane crossing distances are the contours that are shown here, and they represent distances from 2 to 4 radii. So if we have trajectories with different values of θ, which is related to inclination, then if the ring plane crossing distance is 2 radii the closest approach distance to Saturn will range between 1 and 2 radii as shown. Therefore, for a θ angle of 32°, it is possible to cross the ring plane at 2 radii and, in fact, impact Saturn. Going to a larger ring plane crossing of 3 radii, which is about the location of Mimas, you could get, for example, within one-half a radius of the surface of Saturn. If you had the constraint that we currently have, which is 4 radii for the ring plane crossing, or in the vicinity of Enceladus' orbit, it is possible to get as close as within 1.8 radii of Saturn. As shown in the figure, this occurs at a certain value of θ and, as I said, θ starts off parallel to the ecliptic and then increases clockwise, or downward. The ring plane is located near a θ value of about 28°. Therefore, at 30° to 40°, you would pass just under the rings and get as close as possible to Saturn and still maintain the ring plane crossing at 4 radii. A decrease or increase in this angle will change how close you get to Saturn. This figure could be used to locate the best targeting at Saturn in order to get as close to the planet as possible.

DISCUSSION

Fred Franklin Have you done simulation studies to see what mass determinations might be possible? I think the mass of Rhea, for instance, is completely unknown. One wonders if it would not be possible to get, say, close enough to the ring to detect its mass if it were sufficiently great.

Paul Penzo Just flying through the Saturn system will give you some mass information for practically all of the satellites. There is a study going on that determines how well you can find the mass of various satellites for various trajectories. It turns out that for Titan you need not get very close in order to determine its mass to more accuracy than we presently have. For some of the inner satellites, it would be more difficult to do, and we may have to approach Saturn much more closely in order to separate the effect of the inner satellite masses from the effect of the planet's oblateness.

Franklin Can you determine the ring mass?

Penzo It is very difficult. An analysis has been done recently which indicates that to the first order you cannot separate the ring mass from the oblateness effect.

Franklin I think, though, if you went above the ring plane, you might have better success than if you were in the ring plane.

Penzo Yes, intuitively this seems to be the case, and I think that's true. The analysis I saw did not say this, but I would think so. We haven't gone that far into it.

Eshleman It is very difficult to determine the ring mass. If you went through the Cassini division, there is a possibility.

Franklin You might go into the Cassini division and not come out.

Sam Gulkis You did all of this work independent of anything that was going on at Jupiter. I would like to know which of these constraints are actually closed out by putting similar constraints on the Jupiter flyby.

Penzo Sam (Gulkis), Jupiter will affect the trajectory analysis or mission analysis in the sense that currently we allow the trajectory to pass within about 4 Jupiter radii of Jupiter, and that occurs for early arrivals at Jupiter and, correspondingly, early arrivals at Saturn. If that safe distance increases, say to 6 R_J, then you would have to remove the section of early arrival dates. Then we could not get there for the first few months because the distance of close approach to Jupiter is determined by the fact that you must go to Saturn, and the early arrivals at Jupiter require getting close to Jupiter. However, you could still accomplish all of the other mission goals.

Gulkis The targeting is still the same?

Penzo Yes. You simply narrow down the trajectory space that you will get, but you can still accomplish all of your goals.

Gordon Pettengill In figure 5, was Titan also assumed to be approached closely?

Penzo The trajectory that results in the best Earth occultation by Saturn's rings does not contain the Titan before or the Titan after encounter. It is closer to the region of the Titan after encounter, however, than it is to the Titan before encounter.

Pettengill What I am asking is, if one were to select one of those as desirable, are you then throwing away a close Titan approach?

Penzo Yes, that is true. You would certainly be throwing away a Titan before encounter because it requires staying further away from Saturn to satisfy the ring plane crossing constraint. There is a narrow region that occurs directly undernearth the ring plane where you can get very close to Saturn and still maintain a certain distance for ring plane crossing.

Pettengill You say "close to Saturn." Do you mean close to Titan?

Penzo No, close to Saturn. The Titan after encounter, however, is close to that region, and the overlap, if any, has yet to be investigated.

Brad Smith Well, Gordon, we are going to launch two spacecraft and hopefully two will arrive at Saturn.

Pettengill And one will be used for Titan?

Smith That is a possibility.

Robert Soberman: Paul (Penzo), have you had a chance to give any consideration to Al Cook's[1] suggestion that in fact a safe place to cross the ring plane inside of 4 R_S might be through the orbit of Mimas?

Penzo Yes, that was implied on the last figure, where you could maintain the spacecraft at a fixed ring plane crossing distance, such as 3.1 R_S, which is the orbit distance of Mimas. You would have to stay on essentially the curve marked 3 radii in figure 6. So as you selected different values of θ, your distance of close approach to Saturn would change. For Titan before passage, for example, a θ angle of around 60° to 70° would be required, so you would have to pass

[1] A. F. Cook, Smithsonian Astrophysical Observatory, a member of the MJS 77 imaging team.

Saturn at about 2 radii and cross the ring plane at Mimas' orbit. That would result in a Titan before close approach. The Titan after encounter is located near a θ angle of about 35° to 40°, so your closest approach to Saturn would have to be lower. This suggestion puts an added constraint on the trajectory selection in the sense that previously you could encounter Titan with any distance of close approach to Saturn or, equivalently, any ring plane crossing distance. If you insist on also passing through the orbit of Mimas, then you would be forced to fix the ring plane crossing distance at Saturn and also fix the arrival date. Hence, whereas figure 4 shows conditions for a time variation of 2 days, you now would have a specific date on which to both pass through Mimas' orbit and encounter Titan.

William Irvine: The choice of Jovian satellites you might wish to encounter doesn't particularly affect these computations?

Penzo: Not strongly. The time at which you arrive at Jupiter and the time at which you arrive at Saturn are tied together in the sense that the earlier you get to Jupiter, the earlier you will get to Saturn. However, utilizing midcourse corrections, you can vary the relation between the two arrival dates within a couple of days and that is sufficient to allow you to perform the mission analysis at Jupiter and find a Galilean satellite encounter separate from the Saturn analysis.

Smith That, in fact, is a strong constraint, because the period of Titan is something like 16 days, so if you have only a few days to play around with, that definitely controls the satellite opportunities at Jupiter.

Penzo At Jupiter, that's right. However, as it happens, because there are four major satellites of Jupiter, when we do pick a date we are within 1 or 2 days of encountering a satellite at Jupiter.

Smith But the Jovian satellites are not all of equal importance.

Penzo Yes, that's right. Perhaps I should say something about the Jupiter trajectories. The Jupiter analysis is quite different from Saturn's because the Jupiter flyby is constrained to continue on to Saturn, and you fly by Jupiter essentially in the equatorial plane of Jupiter. The close-approach range is from inside Io's orbit out to about halfway between the orbits of Europa and Ganymede. The Io approach occurs early in arrival dates and then disappears. So you can only get Io on early Jupiter encounters— which implies early Saturn encounters— and that amounts to about one-sixth of the total trajectory space that you have available. For the remaining arrival dates, the trajectory past Jupiter increases in closest approach distance and remains outside of Io's orbit.

Irvine How much does your lack of knowledge of the mass of these satellites affect your trajectories?

Penzo At Jupiter it is very important because we must maintain the trajectory to get to Saturn. But once we are at Saturn, the trajectory requirements past Saturn are very free. At Saturn, we are interested in the postencounter orbit determination problem, where we can try to determine the masses, but we are not so interested in the effect of uncertainties in those masses as far as where the trajectory goes past Saturn. If we had to go on to Uranus, of course that adds a tight constraint, which increases the importance of knowing the mass of any Saturn satellites that are closely approached.

Irvine That implies it is not reasonable to aim for Uranus.

Penzo Not necessarily. There are missions being studied. The Saturn accuracy problem I have stated, however, could very well imply that the spacecraft presently being designed for MJS 77 could not carry enough midcourse fuel onboard to get to Uranus.

Dick Wallace There is a long time for small course changes to act. The flight time to Uranus is twice as long as to Saturn.

Penzo The fuel requirements are proportional to the time you are on the trajectory, and you require a couple of years to get to Uranus past Saturn. There are missions being investigated for the post–1977 period to the outer planets, and one particular mission is a Pioneer Saturn/Uranus probe. Figure 7 shows essentially the same impact parameter plane that I showed earlier for the MJS 77 mission, in that the approach direction is from the perpendicular to the plane of the figure. Plotted are the ring plane edges and lines of constant ring plane crossing distance. The points at which you would aim in this plane to get a Saturn probe are marked. You would want to get as close to Saturn as possible in order to minimize a ΔV necessary for deflecting a probe into Saturn, and, if you are interested in the spacecraft continuing on past Saturn, you would want to maintain passage beyond the visible rings as shown. If you want it to continue on to Uranus, then, as I said earlier, for a Pioneer Saturn/Uranus probe, the aimpoint regions for continuing on to Uranus are essentially in the ecliptic plane. The horizontal is the ring plane location. The ecliptic plane passes essentially through the points marked 1979 through 1982, which are the

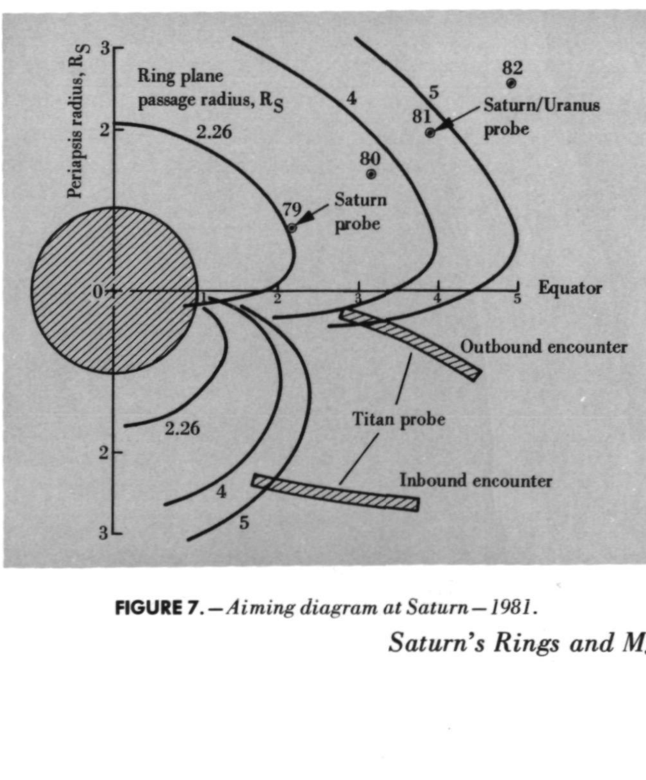

FIGURE 7.—*Aiming diagram at Saturn—1981.*

Saturn-Uranus probe aimpoints. So in 1981, for example, you would have to aim at the point shown.

Eshleman Is that a launch in 1981 you are talking about?

Penzo Yes, a launch in 1981. A launch in 1980 would actually require that the aimpoint be within or on the 4 R_S boundary, and in 1979 it would move in even closer. This indicates that just as you have desirable aimpoints for the Mariner Jupiter/Saturn mission, you have similar aiming regions for missions that go beyond the 1977 Jupiter/Saturn launch. This figure, which is similar to figure 2, was given to me by John Niehoff of Science Applications, Inc., Chicago, who determined the aim region for the Titan 1981 encounters, which are very similar to those of the MJS 77 launch.