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## **SATURN ORBITER DUAL PROBE MISSION**

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### **ABSTRACT**

With the completion of the flybys of Saturn by the Pioneer 11 and Voyager spacecraft in 1979 and 1981 the reconnaissance phase of the Saturn system investigation will be completed. The logical follow on mission is one that provides the capability for detailed long duration observations of the planet and its satellites. This requires a Saturn orbiting spacecraft with remote sensing capability and with maneuvering capability to tour the satellites of Saturn. The described Saturn Orbiter Dual Probe mission and spacecraft combines three systems into a multi-purpose Saturn exploration package that can satisfy the exploration objectives. The spacecraft, as currently envisioned, consists of

- (1) Saturn Orbiter
- (2) Saturn Probe
- (3) Titan Probe or Lander

This single spacecraft provides the capability to conduct *in situ* measurements of the Saturn and Titan atmospheres, and, possibly the Titan surface, as well as a variety of remote sensing measurements. The remote sensing capabilities will be used to study the surfaces, interiors and environments of Saturn's satellites, the rings of Saturn, Saturn's magnetosphere, and synoptic properties of Saturn's atmosphere.

Based on the 1975 report of the Space Science Board (1975), the recommended post-Voyager Saturn exploration objectives are:

- (1) Intensive investigation of the atmosphere of Saturn including in situ measurements of the chemical composition made with an atmospheric probe.

- (2) The determination of regional surface chemistry and properties of the surface features of satellites and properties of ring particles.
- (3) Intensive investigation of the satellite Titan.

These objectives require, in addition to a Saturn orbiting spacecraft, a Saturn atmospheric probe and a Titan atmospheric probe or lander.

This paper discusses an example Saturn Orbiter Dual Probe (SOP<sup>2</sup>) mission that satisfies these exploration objectives. The example spacecraft is a multi-purpose Saturn exploration package consisting of three separate spacecraft systems. These systems are:

- (1) Saturn Orbiter
- (2) Saturn Probe
- (3) Titan Lander\*

The Saturn Orbiter is the bus vehicle for the Saturn Probe and Titan Lander providing all propulsive maneuver capability necessary to deliver each of these vehicles. The Saturn Probe is deployed from the Saturn approach trajectory and the Titan Lander is deployed from Saturn orbit. Based on Jupiter Orbiter Probe (JOP) spacecraft studies by JPL and Titan Lander studies by the Martin Marietta Corporation, the necessary mass for each subspacecraft system is:

- |   |         |
|---|---------|
| (1) Saturn Orbiter (less propellant tanks and propellant) | ~590 kg |
| (2) Saturn Probe (no propulsive capability)               | ~200 kg |
| (3) Titan Lander (no propulsive capability)               | ~225 kg |

The launch time period under consideration is 1986 utilizing a single space shuttle launch with the Interim Upper Stage (IUS) booster. This launch year should allow adequate time to incorporate knowledge gained by the Voyager flybys into the SOP<sup>2</sup> spacecraft design. This is of particular importance to the design of the Titan Lander where the current range of Titan atmosphere models is large. Based on a 1986 launch, the Saturn delivery mass capability for standard ballistic trajectories is inadequate to conduct the desired mission. A single shuttle launch is capable of delivering less than 900 kg to Saturn in this mode. Considering the orbiter propellant and tankage necessary to achieve Saturn orbit and perform all other necessary propulsive maneuvers, a delivery mass of approximately 2000 kg or greater is required. The exact mass requirement varies as a function of Saturn approach speed,  $V_{\infty}$ . It

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\*This paper refers to the Titan vehicle as a lander, however, a less complicated atmospheric probe is also under consideration

would be possible with multiple shuttle launches (probably 3) with on-orbit stacking of IUS to provide the required delivery mass capability with a standard ballistic trajectory mode. Other Earth-Saturn transfer modes investigated to achieve an adequate Saturn delivery mass capability include gravity assist techniques and low thrust, ion drive. The gravity assist mode (VEGA or  $\Delta$ VEGA) utilizes swingbys of Venus and/or Earth to add energy to the spacecraft orbit. Inherent to the VEGA or  $\Delta$ VEGA mode is a long flight time of 7.5 to 8 years in addition to the necessity of executing an *additional* propulsive maneuver near Earth of approximately 2 km/s. Discussions of these gravity assist techniques are contained in Roberts (1975) and Martin Marietta Corporation (1976). The low thrust, ion drive mode also has long flight times, 7 to 8 years, if the current baseline Encke '87 system parameters are used. System performance improvements could however reduce flight time. In comparison to these delivery modes a combined ion drive/gravity assist mode utilizing an Earth swingby was found to provide the greatest Saturn delivery mass capability. Using this technique, mass delivery capabilities in excess of 2800 kg with flight times of 6 to 8 years are possible. Table 1 summarizes these different Earth-Saturn transfer modes. The

Table 1. 1986 Earth-Saturn Transfer Modes

Option	Saturn Delivery Mass, * kg	Saturn Flight Time, yr	Saturn Approach Speed, $V_{\infty}$	Mission
Direct Ballistic	< 900	5.7	5.4 km/s	Flyby and probe or lander mission possible
Ballistic Gravity Assist	2400 - 2600	7 - 8	5.9 km/s	Baseline Mission possible
Ion Drive	2100 - 2200	7 - 8	6.0 - 5.0 km/s	Baseline Mission possible
Ion Drive/ Gravity Assist	2800+	6 - 8	7.5 - 5.5 km/s	Baseline Mission possible

\*Saturn Approach Mass, Not Mass in Orbit

baseline SOP<sup>2</sup> mission incorporates the low thrust, ion drive mode into its design. Major events of the baseline SOP<sup>2</sup> mission are described in Table 2 and illustrated in Figure 1. Spacecraft launch occurs in 1986 using a single space shuttle/IUS combination. The spacecraft consists of the Saturn Orbiter/Saturn Probe/Titan Lander combination and an ion drive propulsion module. The ion drive module provides low thrust capability for the initial 2 1/2 to 3 1/2 years after launch. at which time it is jettisoned and the spacecraft continues on a ballistic trajectory to Saturn.

Approximately 65 days before Saturn encounter the Saturn Probe is separated from the Saturn Orbiter on a pre-established trajectory to enter the Saturn atmosphere. The separation conditions had previously been established by propulsive maneuvers executed by the Saturn Orbiter. Following probe separation, approximately 60 days before encounter, the orbiter executes another propulsive maneuver to deflect its trajectory away from Saturn impact. This deflection is accomplished to establish a periapsis altitude of four Saturn radii ( $4 R_S$ ) and to optimize the encounter time to maximize the Saturn Probe to Saturn Orbiter relay link data return capability. Figure 2 is an illustration of the probe entry and the orbiter passing overhead receiving the relay link.

Targeting options for the entry probe are best described by referring to the representative B-plane plot for Saturn Probe targeting contained in Figure 3. Saturn approach is from the north with a major portion of the planet being illuminated. The shaded band from the top to the bottom of the figure is the region of aim-points which result in an entry on the night side of the terminator. To the right of the band is a region of aim-points which miss Saturn entirely while to the left is a region of aim-points which result in entry on the daylight side of the terminator. The dot pattern shading in the lower right hand corner area of the plot is the region of trajectories which pass through the rings of Saturn. The curved edge of this region represents the innermost visible edge of the crepe ring. Three arcs (dashed lines) representing targeting for entry angles of -10, -20, and -30 degrees are shown parallel to the terminator. Another set of lines labelled from 15°N through 10°S are target points for entry at various latitudes on Saturn. The line labelled 0° is the equator. Any trajectory aimed between the equator and the edge of the crepe ring must necessarily pass through the ring plane and therefore through any ring particles as yet unobserved inside the crepe ring. Therefore, it is preferable, if possible, to land in the northern latitudes. For entry angles more shallow than -13 deg, it is not possible to land north of the equator. In order to avoid having a steeply inclined orbit and possible

Table 2. Baseline Mission Scenario

Time Relative to Probe Entry	Events	Comments
E - 750 days	Pre-Saturn Navigation Maneuver	$\Delta V \approx 5$ m/s
E - 70 days	Pre-Probe Separation Nav. Maneuver	$\Delta V \approx 5$ m/s
E - 65 days	Saturn probe separation from bus	Mechanical separation
E - 60 days	Bus deflection maneuver	$\Delta V = 77$ to $100$ m/s (probe does not have maneuver capability)
E - 4 to 10 days	Pre-insertion Nav. Maneuver	$\Delta V = 10$ m/s
E + 0	Saturn Probe entry	Entry angle of $7.5$ deg
E + 1/2 hr	Orbiter overhead from probe	Orbiter and probe have same radius vector
E + 2 1/2 hr	Insertion into Saturn orbit of periapsis $4 R_S$ and period $159.4$ days	$\Delta V = 990$ to $1963$ m/s
E + 79.7 days	Periapsis raise from $4$ to $19 R_S$	$\Delta V = 590$ m/s
E + 85 to 100 days	Pre-Titan Nav. Maneuver	$\Delta V = 20$ m/s
E + 159.4 days	Titan encounter pump-down and/or plane change	Saturn orbit period reduced to $31.9$ days
E + 165 to 180 days	Pre-Titan Nav. Maneuver	$\Delta V = 20$ m/s
E + 191 days	Titan lander approach and entry	$40$ kg of landed science; $225$ kg Titan approach mass
E + 0.5 to 1 year	Satellite/ring tour	$\Delta V = 50$ m/s

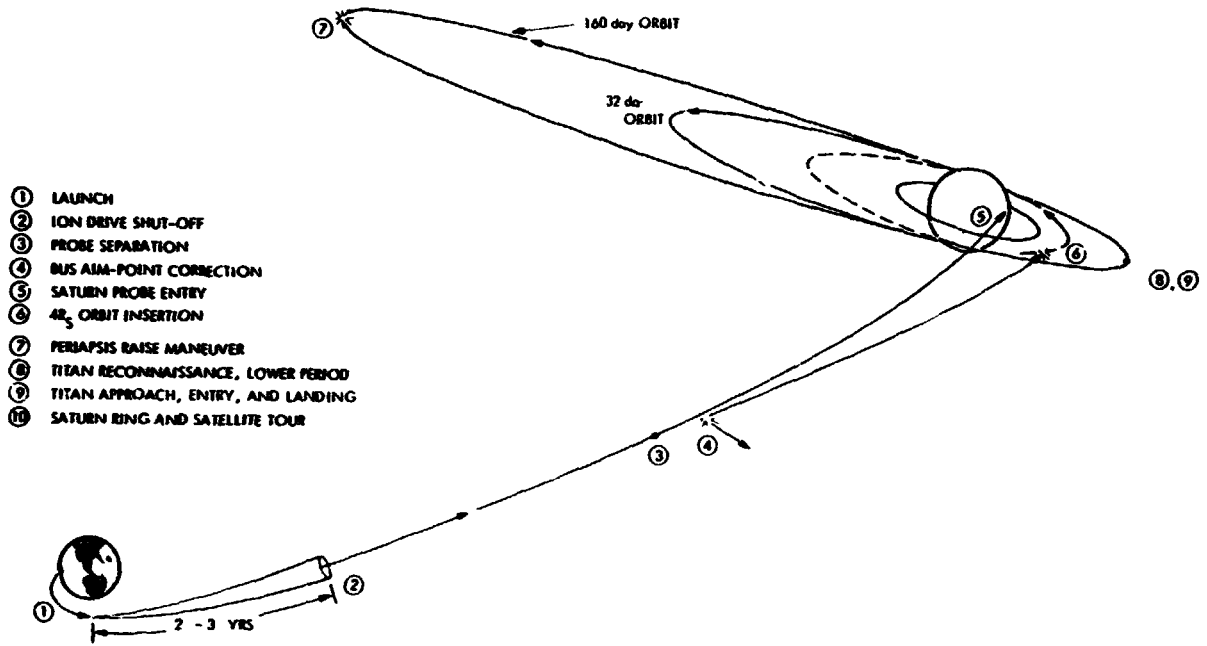


Figure 1. Baseline Mission Scenario

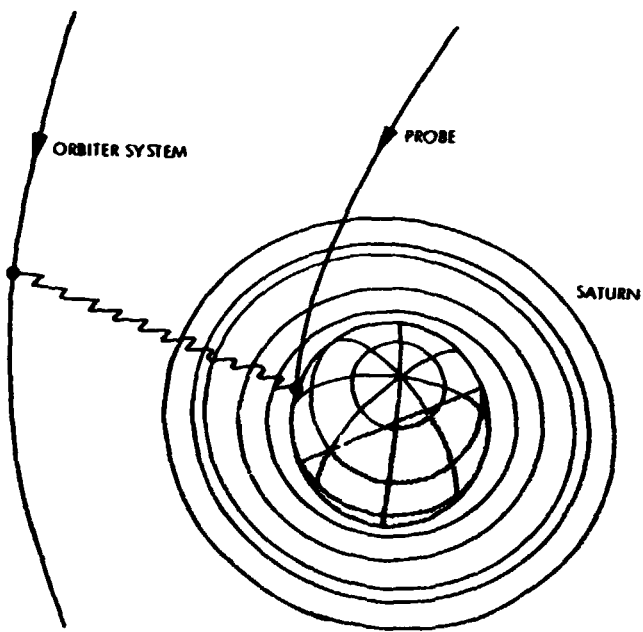


Figure 2. View from North Ecliptic Pole of Probe Entry

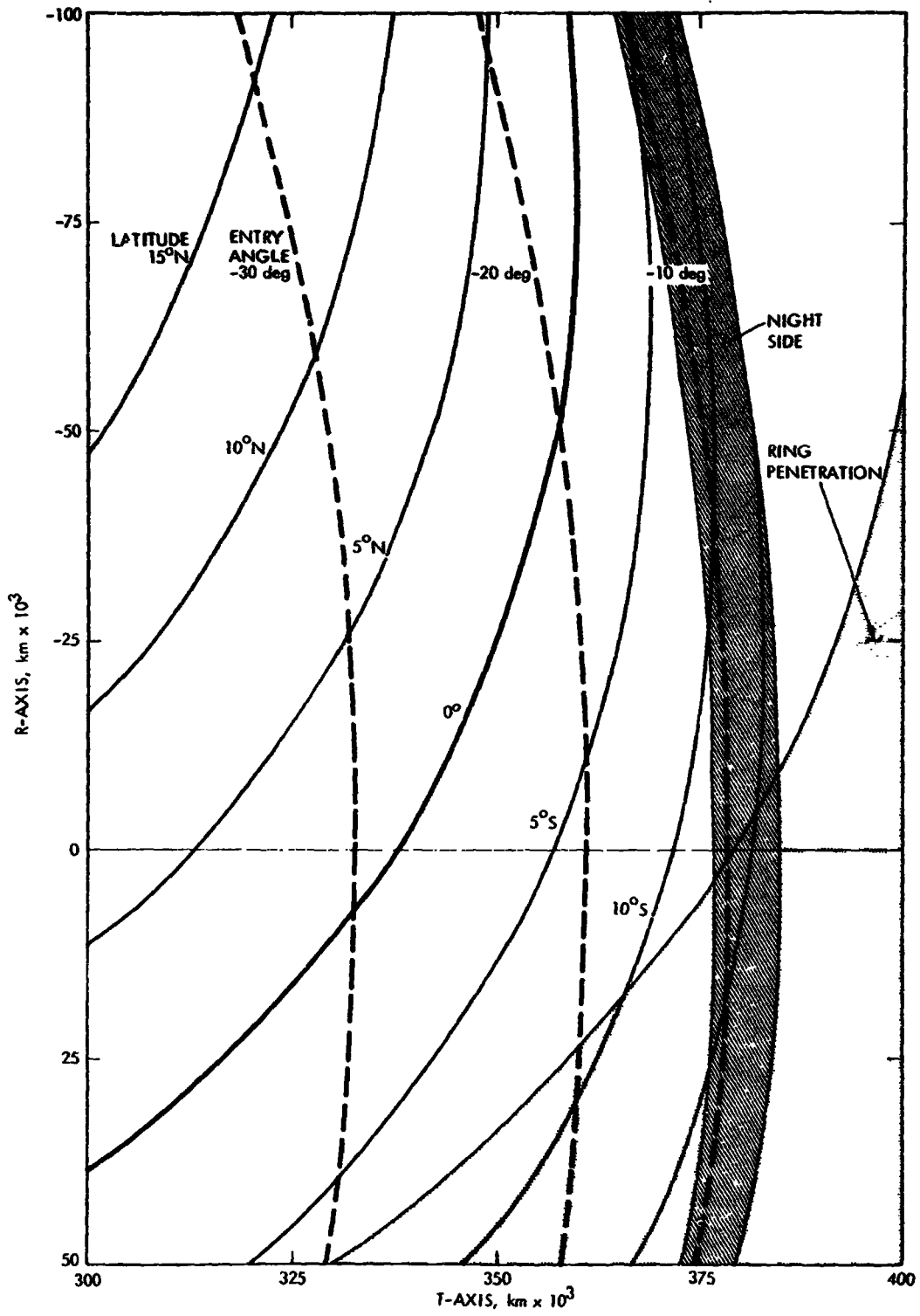


Figure 3. Saturn B-plane Mapping, Saturn Probe Entry Design

requirements for large plane changes, it is preferable to land as close as possible to an R value of 0, that is, near the lower part of the plot. A good aim-point for this approach trajectory would thus be for an entry angle of about -30 degrees, and an entry just north of the equator.

The Saturn entry environment is less severe than the Jupiter environment with the entry velocity being 27 km/s instead of the 48 km/s at Jupiter. Entry can occur at relative flight path angles of -6 to -40 degrees. The maximum axial load in this range of flight path angles is approximately 360 Earth Gs and a maximum dynamic pressure of approximately  $600 \text{ kN/m}^2$  as compared to JOP's nominal of 385 Earth Gs and  $800 \text{ kN/m}^2$ . The convective heating rate is approximately 40% of a JOP entry. Using a JOP staging scheme the Saturn entry to a pressure altitude of 10 bars can be up to two hours duration which places stringent relay requirements on the orbiter as it flies overhead. Figure 4 illustrates representative relay link margins as a function of periapsis altitude and indicates the rationale for selecting a periapsis altitude of  $4 R_S$ . A zero link margin is defined as that signal to noise ratio, 10 dB, required to support 100 bps (a preliminary JOP specification).

Approximately 2 1/2 hours after Saturn Probe entry the orbiter propulsion system is used to slow the spacecraft, inserting the Saturn Orbiter/Titan Lander systems into a Saturn orbit with periapsis radius of  $4 R_S$  and an orbit period of approximately 160 days. This is illustrated in Figure 5 as well as other pre-Titan landing major events. Near the first apoapsis, ( $\approx 184 R_S$ ), approximately 80 days after orbit insertion, an orbiter propulsive maneuver is executed to increase the periapsis radius to  $\approx 19 R_S$  in preparation for the first Titan encounter to occur approximately 80 days later. During this Titan encounter, the influence of Titan's gravitational field is used to "pump down" the orbit period to 31.9 days (twice the Titan period) and possibly change the plane of the orbit. During one of the subsequent Titan encounters the Titan Lander is separated from the orbiter on a pre-established entry trajectory for Titan entry and landing. The orbiter then executes a propulsive deflection maneuver similar to that performed in support of the Saturn Probe deployment. During Titan entry and landing, data are relayed to the Saturn Orbiter for playback to Earth. If the Titan Lander is intended to survive only a few hours after landing, the orbiter could be released after receiving the lander data to begin its satellite/ring tour. If the lander is intended to survive for months after landing, the orbiter will continue its Titan encounters to receive additional data from the lander. This assumes there will not be any direct playback between the Titan Lander and Earth ground stations.



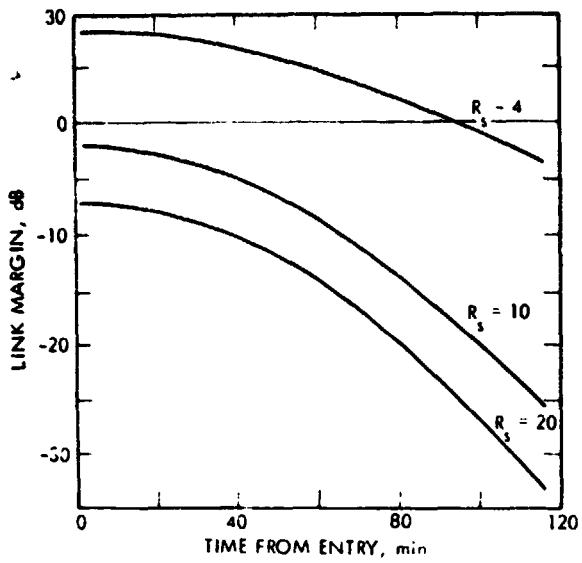


Figure 4. Link Margin vs Time from Entry (Periastron Variation)

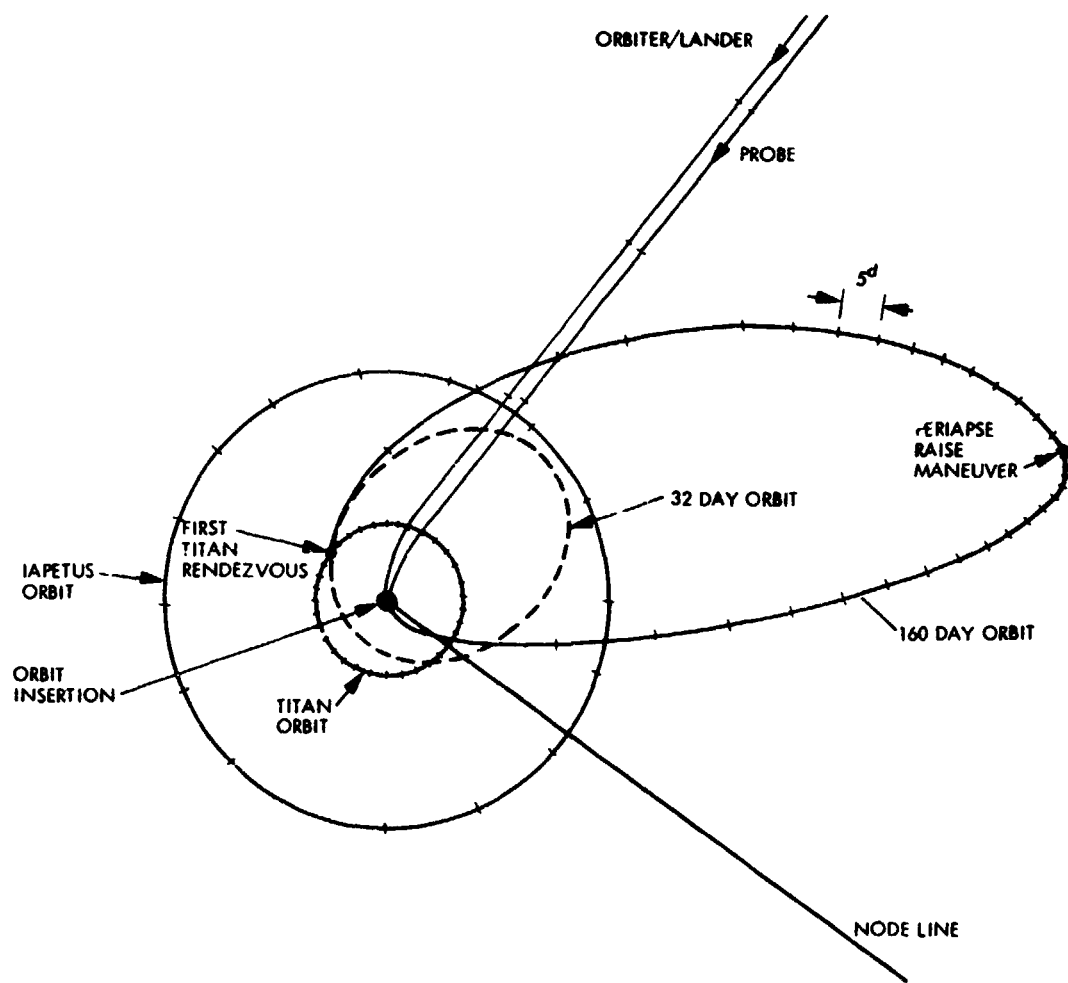


Figure 5. Pre Titan Landing Orbit Sequence

Another option for the Titan Lander would be to provide it with a propulsive and RF command reception capability. After separation from the orbiter the lander would, using its propulsion system, insert itself into a Titan orbit. After several revolutions, during which Titan is observed from orbit, the lander enters Titan's atmosphere and lands on its surface sending back data to the Saturn Orbiter via relay link. In this option the Saturn Orbiter would probably be in a nearly circular orbit at Titan distance ( $\approx 20 R_S$ ) but inclined with respect to Titan's orbit. This option would significantly increase the Saturn delivery mass delivery requirements and could mean even longer flight times or require a combination of low thrust and gravity assist modes.

Titan entry speeds for delivery from Saturn orbit range from 2.4 to 7 km/s. For the orbit previously described (periapsis radius of  $19 R_S$  and an orbit period of 31.9 days) the entry velocity is approximately 2.8 km/s. For comparison purposes, the entry speed for delivery from Titan orbit varies between 1.7 and 2.4 km/s.

Titan appears to be the least difficult of any of the major Solar System bodies on which to mechanize a landing. It is expected that a Titan soft landing can be achieved with a lander vehicle of considerably less complexity than, say, the Viking or Surveyor vehicles. The current state of knowledge of Titan's atmosphere will probably not permit the design of a single cost effective lander for all atmosphere models. Surface pressure, just one of many parameters characterizing the Titan atmosphere, differs by a factor of 500 among the four models being considered, Figure 6. The Titan occultation data from the Voyager flybys in 1981 will be most important in hopefully reducing the range of atmosphere models that must be considered for SOP<sup>2</sup>. Titan landers can probably be configured without complex attitude or altitude control systems, the most complex device required being a parachute and/or simple touchdown cushion. For the super-thick Titan atmosphere model not even a parachute is required.

Descent trajectory profiles for the four atmosphere models are shown in Figure 7 for lander delivery from the previously described Saturn orbit. The ballistic coefficient of  $100 \text{ kg/m}^2$  represents a 225 kg lander with a  $2.25 \text{ m}^2$  aeroshell. For these trajectories the maximum axial load is significantly less than 10 Earth Gs, which is a representative upper limit that would not impact lander design. In fact, for an entry speed of 2.9 km/s flight path angles up to  $-90$  deg still do not result in axial loads of 10 Earth Gs for any of the atmospheres. The shallowest entry angle is approximately  $-25$  deg where skipout occurs. The maximum axial load experienced in

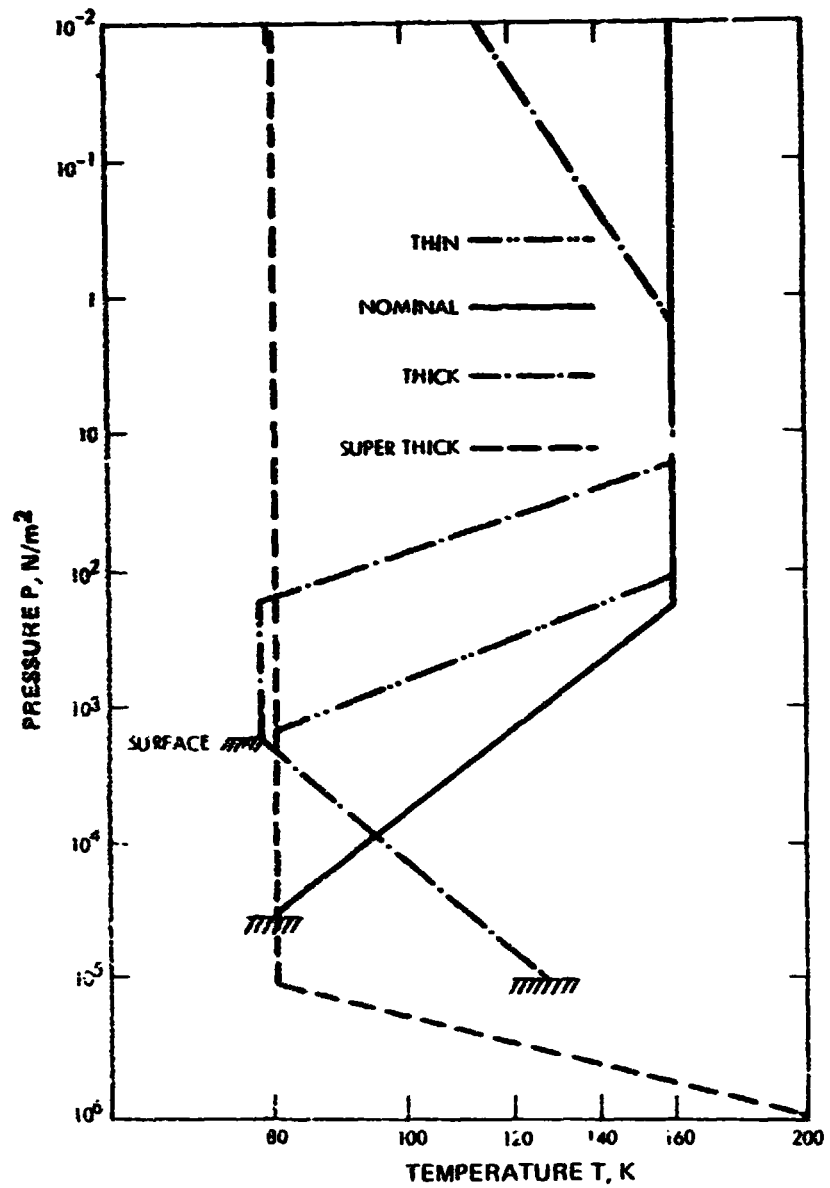


Figure 6. Pressure Temperature Profiles of Engineering Models of Titan's Atmosphere

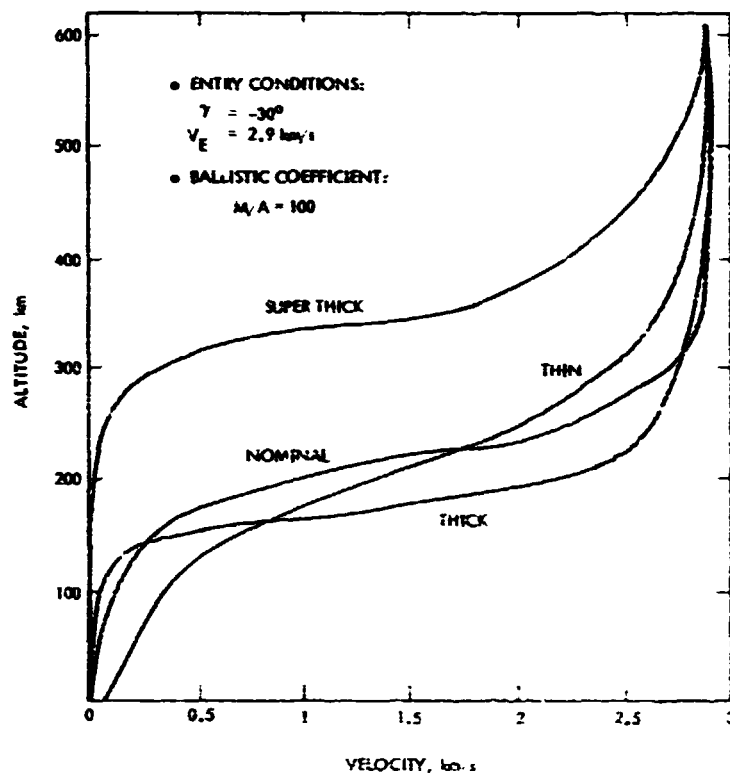


Figure 7 Descent Profiles

the nominal atmosphere as a function of entry speed, flight path angle and ballistic coefficient is illustrated in Figure 8. For reference the Viking value is shown on the chart. The peak heating rate and integrated heating input has a minor effect on lander mass. Considering worst case values requires a heat shield of approximately 5% of the lander mass.

Terminal descent to a landing with a maximum touchdown velocity of 10 mps is possible in all atmospheres with only a parachute. In the super thick atmosphere the parachute primarily provides attitude control during descent. In all cases the parachute can be deployed at a 2 km altitude. The thin atmosphere provides the worst environment for terminal descent requiring the largest parachute to achieve an acceptable (<10 mps) touchdown velocity. It turns out that the parachute size needed for the thin atmosphere is almost the same size as the Viking parachute. The variation in touchdown velocity with parachute size or ballistic coefficient is illustrated in Figure 9. It is readily apparent that parachute size becomes important only if the thin atmosphere is considered.

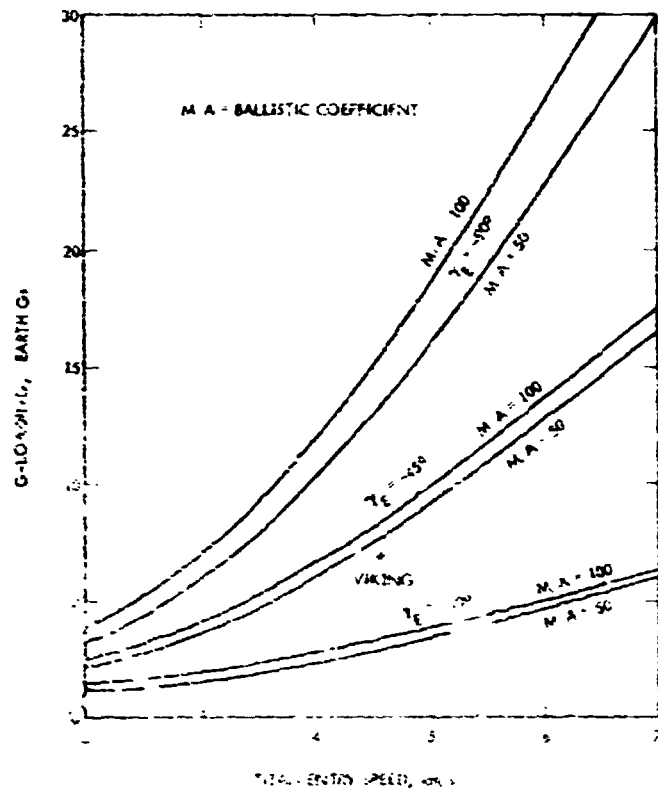


Figure 8. G-loading for Total Entry, Normal Atmosphere

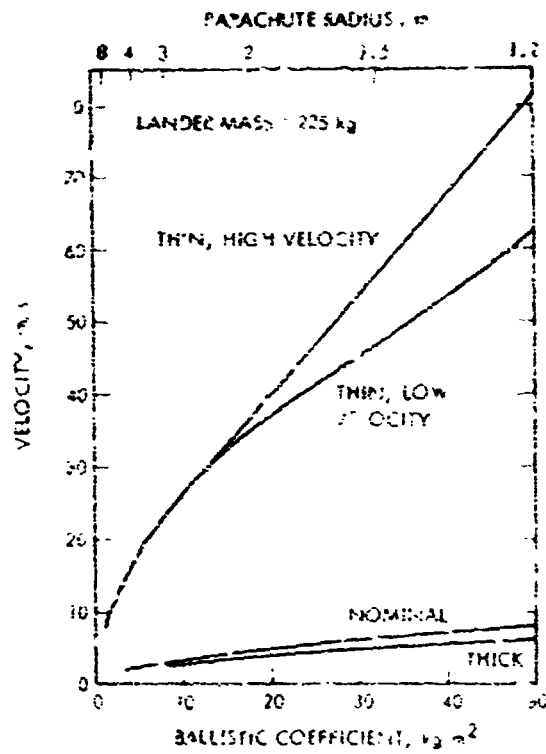


Figure 9. Terminal Velocity

Flight times from entry to touchdown vary from 30 min to in excess of 4 1/2 hours depending on the atmosphere, aeroshell ballistic coefficient, parachute size and altitude of parachute deployment. If the model atmosphere range can be narrowed down it is possible to control the time spent in descent by proper sizing and staging strategies.

Data transmission from the Lander would be relayed through the orbiter vehicle as it passes by Titan. If the lander were designed to survive only a few hours after landing this relay would take place during the initial overflight of the orbiter during entry and landing. If the lander were designed to survive for an extended period of time the orbiter would pass by Titan periodically to receive the relay from the lander. Figure 10 illustrates the variation in orbiter range and elevation as viewed by a lander on the surface of Titan at the anti-Saturn point, a Saturn Orbiter in a 32 day period, and  $20 R_S$  periapsis radius orbit that is coplanar with the orbit of Titan. Line of sight from lander to orbiter is maintained for several days around closest approach for relay data transmission purposes.

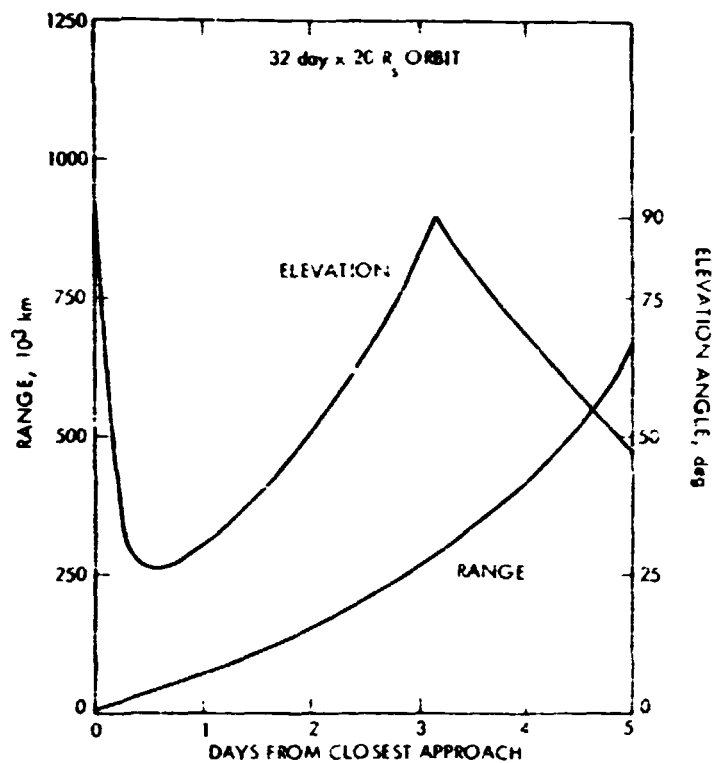


Figure 10. Saturn Orbiter - Titan Range, Elevation, 32 Day x  $20 R_S$  Orbit

In order to conduct a satellite tour it is necessary to make orbit changes using gravity assist pumping and cranking techniques. Of all the Saturn satellites Titan is the only one that can be used effectively for these purposes. Large period changes of 100 days are possible with a single encounter as are inclination and apsidal rotation changes of 10s of degrees per encounter. With this capability a tour is possible; however, encounters with other satellites of Saturn will have to be found on trajectories which are targeted back to Titan. Reference 2 (Roberts, 1975) contains a detailed discussion of Titan pumping and cranking capability and also some examples of possible satellite tours.

The information contained in this paper was derived primarily from the results of the 1977 Saturn Mission Options Study (Wallace, 1977). This reference contains additional details, parametrics and considerations for interested readers.

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## DISCUSSION

D. MORRISON: Have you gone through any exercises to see how many satellite encounters you might get in a year or 18 months in orbit?

R. RUDD: In a year's time, right now I would be guessing, but I would say it's like 3 or 4, not including Titan.

D. MORRISON: One every second orbit or something of that sort?

J. CALDWELL: In what ways do you get hurt if you design a probe for a very thin atmosphere and it turns out to be thicker than you expected when you designed it?

D. HERMAN: You have to use the orbiter as a relay, so if the descent rate is very, very slow, it's conceivable that you lose communication before you can get to the lower atmosphere.

D. MORRISON: At what pressure level does the probe become subsonic and start taking data? That's extremely important for us because one of the things we want to know from this group is whether a Titan probe is worthwhile. If there is a possibility of a very thin atmosphere, we don't know if we can get any probe data at all.

R. RUDD: I don't have an answer to that.

D. HUNTEN: We need to know, given an atmosphere, let's say take two extremes, one that's practically pure hydrogen and one that's practically pure nitrogen, when do you reach Mach 1 slowing down, is it at 1 mbar, 10 mbars, or a hundred millibars? For Jupiter, it's 100 mbars, and that's disappointing. It's presumably much less for Titan, but the question is, how much less.

R. RUDD: I will try to get the answer from JPL. (Answer: In the range of atmospheres that were studied, the probe reaches Mach 1 at 2-5 mbar.)

J. CALDWELL: Is it possible to arrange the orbit such that you intersect Titan at different points in Titan's orbit, so that you don't always have to see the same side of Titan.

R. RUDD: Yes. That will happen with apsidal rotations.

D. MORRISON: You'd have to rotate the line of apsides, which is a step-wise process, in order to look at different sides. You can't, given just one intersection with Titan, arbitrarily choose to intersect at some completely different point in its orbit the next round.