# INCORPORATING ICY SATELLITE FLYBYS IN THE CASSINI ORBITAL TOUR

**Aron A. Wolf***

The Cassini mission to Saturn employs a Saturn orbiter and a Titan probe to conduct an intensive investigation of the Saturnian system. The Cassini orbiter flies a series of orbits, incorporating flybys of the Saturnian satellites, called the "satellite tour." During the tour, the gravitational fields of the satellites are used to modify and control the orbit, targeting from one satellite flyby to the next. The tour consists mostly of Titan flybys, because Titan is the on] y satellite massive enough to make the large modifications in a spacecraft's orbit needed in the tour, and because Titan is the satellite of highest priority for science observations. However, close observation of Saturn's smaller icy satellites is also a high-priority objective, as well as one that is difficult to achieve.

Because the less massive icy satellites are capable of making only small changes in the spacecraft's orbit, flybys of icy satellites must be achieved essentially "on the way" from one Titan fl yby to another. That is, when departing Titan enroute to an icy satellite flyby, the spacecraft must be in an orbit very much like one which returns it directly to Titan; if it is not, the icy satellite flyby cannot change the orbit enough to return the spacecraft to Titan. This makes achieving close flybys of icy satel lites a chal lenge requiring new methods in design of satellite tom trajectories.

Opportunities for close icy satellite flybys are found using numerical search techniques. Because the numerical search can bc time-consuming, analysis is done to reduce the set of orbits which must bc searched to a manageably small sire.

The set of transfer orbits between Titan flybys which are of primary interest in Cassini tours is relatively small. The need to continually re-encounter Titan levies important constraints on the design of Cassi n i tours. Because of the need to achieve a diverse set of scientific objectives (including a large number of Titan flybys), it is impractical to consider using orbits whose periods arc greater than about 60 - 70 days during most of the tour, or to allow the time between Titan flybys to be greater than 100 days, except during portions of the tour dedicated to achieving multiple Saturn occultations. The set of Titan-Titan transfer orbits of practical interest for the design of Cassini tours is shown in Table 1. Analysis of how to incorporate c1osc flybys of icy satellites in the tout can be restricted to this set of orbits.

Two conditions must be satisfied in order for a targeted icy satellite flyby to occur: the spacecraft's orbit must intersect the satellite's orbit, and the satellite must be physicall y present at the time the spacecraft arrives at its orbit. in order for the spacecraft to intersect the satellite's orbit, it is necessary (but not sufficient) for the spacecraft's periapse to bc lower than the satellite's apoapse.

The $V_\infty$ magnitude at Titan varies by a few hundred m/s throughout the tour - for these purposes, it can be considered to be fixed. For each transfer orbit shown in Table 1, it is possible to determine the spacecraft's apoapsis and periapsis from the spacecraft's orbital period, inclination, and the magnitude of $V_\infty$ at Titan. This determines whether it is possible for the spacecraft's orbit to intersect the orbits of each of the icy satellites for all of the transfer orbit types which might be used in the tour.

All the icy satellites' orbits except for that of Iapetus lie close to Saturn's equator. This means that when the spacecraft's orbit is inclined more than a degree or so to Saturn's equator, any intersection of the spacecraft's and satellite's orbits must occur near one of the spacecraft's two orbital nodes. The other node must be near Titan's orbital radius, since the orbit lead either from or toward a Titan flyby. The transfer angle between the Titan and icy satellite flybys is then an odd integer multiple of 180 deg. It is possible to determine the specific value of incl inat ion (from the period and the $V_\infty$ magnitude at Titan) required to place the spacecraft's orbital node at the orbital radius of an icy satellite, as shown in Table 2.

A numerical search is then carried out to find icy satellite flyby opportunities for the small set of Titan-Titan transfer orbits for which such opportunities can exist. For each such transfer orbit, t imes of departure from Titan are found which result in intersection of the spacecraft's orbit with that of the icy satellites at times when the icy satellites are physically present at the point of intersection.

However, it is not necessary to depart Titan precisely at one of the times found by this search in order to fly by an icy satellite. Close flyby of an icy satellite can be achieved as long as departure from Titan occurs during a "window" of time surrounding the instantaneous departure time found by the numerical search. The width of the window is determined by the gravitational assist available from the icy satellite and the amount of AV required to target to the icy satellite flyby.

An example is shown in Table 3, illustrating a Dione flyby occurring on a resonant Titan-Titan transfer. For this example, the nominal orbital period is 23.9 days ( 1.5 x Titan's orbital period); the spacecraft completes 2 revolutions about Saturn and Titan completes 3 revolutions about Saturn in 47.9 days between two successive Titan flybys. The minimum flyby altitude at Dione is assumed to be 1000 km for the purposes of this discussion.

**Table 3: Departure time "Window" from Titan to Dione**

| Titan Departure Time | Titan-Dione Period (days) | Dione-Titan Period (days) | Titan-Dione Flight Time (days) | Dione-Titan Flight Time (days) | Total Flight Time (days) | Dione flyby altitude (km) |
|---|---|---|---|---|---|---|
| 5/2/2005 09:51 | 24.1 | 23.7 | 26.3 | 21.6 | 47.9 | 1000 |
| 5/2/2005 15:24 | 23.9 | 23.9 | 26.1 | 21.8 | 47.9 | 12100 |
| 5/2/2005 20:32 | 23.8 | 24.1 | 25.9 | 22.0 | 47.9 | 1000 |

The instantaneous departure time found by the numerical search method is 15:24 on 5/2/2005. This is the center of the window; i.e. it is possi ble to depart Titan at this t ime with a period of 23.9 days, fly by by Dione 26.1 days later, and return to Titan without changing orbital period. The Dione flyby altitude is high (too high for close observations, in fact) because no gravity assist is required from Dione.

However, if departure from Titan is about 5.5 hours earlier the conditions change slightly. A period of 24. I days is needed to arrive at Dione. in order to return to Titan 47.9 days after departure, the Dione flyby must reduce period from 24.1 to 23.7 clays, requiring a flyby altitude of 1000 km at Dione.

The situation is reversed if departure from Titan is about 5.5 hours later - the period required to reach Dione is 23.8 days, and a 1000-km flyby of Dione is required to *increase* period to 24.1 days in order to return to Titan 47.9 days after departure.

So, in order to be able to return to Titan without requiring Dione flyby altitudes less than the 1000-km minimum, orbital period upon departure from Titan must be 23.9 ±. 2 days. Orbital period lies within this range for departure times within ±5 hr. of 15:24:00 on 5/2/2005. This window of departure times from Titan corresponds to an arc of about 9 deg. in the orbit of Titan.

Windows ate smaller for less massive icy satellites. It is possible to calculate window widths for all the icy satellites for all of the orbits in Table 1.

The instantaneous departure times found by numerical searching combined with calculations of window widths tell a tour designer the start anti end times of opportunities to depart Titan for flybys of all the icy satellites. The tour designer can use this information to determine whether it is possible to target to a c1osc icy satellite flyby from any Titan flyby. These methods have been successfully employed in the design of several sample Cassini tom including the current Cassini "reference tour".

**Table 1: Titan-Titan transfers which can be used to achieve targeted icy satellite flybys (cent'd)**

| Sequence Name | Sequence Description | # of Complete SIC Revs Between Flybys | Time Between Flybys (days) | S/C Orbit Period for V∞=5.55 km/s (days) | S/C Orbit Periapsis Radius for V∞=5.55 (Rs) | S/C Orbit Apoapsis Radius for Vinf=5.55 (Rs) | Mimas | Enceladus | Tethys | Dione | Rhea | Hyperion | Iapetus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **High-inclination** | **(flight time between 15 - 96 days, Period between 6 - 16 days, 5** S/C **revs)** | | | | | | | | | | | | |
| REST3_SC8 | **Resonant, 3 Titan revs: 8 S/C** revs | 8 | 47,84 | 5,98 | ** | ** | x | x | x | x | | | - |
| REST2_SC5 | **Resonant, 2 Titan revs: 5 S/C** revs | 5 | 31.89 | 6.38 | ** | ** | x | x | x | x | | | - |
| REST3_SC7 | **Resonant, 3 Titan revs :7 S/C revs** | 7 | 47.84 | 6.83 | ** | ** | x | x | x | x | | | - |
| REST4_SC9 | **Resonant, 4 Titan revs :9 S/C** revs | 9 | 63.78 | 7.09 | ** | ** | x | x | x | x | | | - |
| REST1_SC2 | **Resonant, I Titan rev: 2S/C revs** | 2 | 15.95 | 7.97 | ** | ** | x | x | x | x | x | | - |
| REST5_SC9 | **Resonant, 5 Titan revs :9 S/C revs** | 9 | 79.73 | 8.86 | ** | ** | x | x | x | x | x | | - |
| REST4_SC7 | **Resonant, 4 Titan** revs: 7 S/C revs | 7 | 63.78 | 9.11 | ** | ** | x | x | x | x | x | | - |
| REST3_SC5 | **Resonant, 3** Titan **revs :5 S/C revs** | 5 | 47.84 | 9.57 | ** | ** | x | x | x | x | x | | - |
| REST5_SC8 | **Resonant,** 5 Titan revs :8 S/C revs | 8 | 79,73 | 9.97 | ** | ** | x | x | x | x | x | | - |
| **REST2_SC3** | **Resonant, 2 Titan revs :3 S/C revs** | 3 | 31.89 | 10.63 | ** | ** | x | x | x | x | x | | - |
| REST5_SC7 | **Resonant, 5 Titan revs: 7 S/C** revs | 7 | 79.73 | 11.39 | ** | ** | x | x | x | x | x | | - |
| REST3_SC4 | Resonant, 3 Titan revs: 4 S/C revs | 4 | 47.84 | 11.96 | ** | ** | x | x | x | x | x | | - |
| REST4_SC5 | Resonant, 4 Titan revs: 5 S/C revs | 5 | 63.78 | 12.76 | ** | ** | x | x | x | x | x | | - |
| REST5_SC6 | Resonant, 5 Titan revs :6 S/C revs | 6 | 79.73 | 13.29 | ** | ** | x | x | x | x | x | | - |
| REST6_SC7 | Resonant, 6 Titan revs :7 S/C revs | 7 | 95.67 | 13.67 | ** | ** | x | x | x | x | x | | - |
| REST1_SC1 | Resonant, I Titan rev : 1 S/C rev | 1 | 15.95 | 15.95 | ** | ** | x | x | x | x | x | x | - |

**** = Values are different for each icy satellite, because a 180 deg. transfer is assumed. See Table X.**

# Table 2: Periapsis radius and inclination required for 180 deg. transfer

| V∞=5.55 km/s | | | | | | | INCLINATION FOR 180 DEG. TRANSFER (DEG) | | | | | | | | PERIAPSIS FOR 180 DEG. TRANSFER (RS) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sequence Name | Time of Flight (d) | #Titan Revs | # S/C Revs | S/C Period (d) | Titan/ S/C Revs | Rp (Rs) Inc.=O | Mimas | Enceladus | Tethys | Dione | Rhea | Titan | Hyperion | Iapetus | Mimas | Enceladus | Tethys | Dione | Rhea | Titan | Hyperion | Iapetus |
| **INCLINED SEQUENCES** | | | | | | | | | | | | | | | | | | | | | | |
| REST3_SC8 | 47,84 | 3 | 8 | 5.98 | 0.38 | 0,0 | 3.5 | 84.2 | 84.7 | 85.2 | - | | | | 3.1 | 4.1 | 5.2 | 7.3 | | | | |
| REST2_SC5 | 31.89 | 2 | 5 | 6.38 | 0.40 | 0.1 | 8.9 | 80.1 | 81.0 | 81.8 | - | | | | 3.0 | 4.0 | 5.1 | 7.0 | | | | |
| REST3_SC7 | 47.84 | 3 | 7 | 6.83 | 0.43 | 0.2 | 4.2 | 76.0 | 77.2 | 78.4 | - | | | | 3.0 | 4.0 | 5.0 | 5.7 | | | | |
| REST4_SC9 | 63.78 | 4 | 9 | 7.09 | 0.44 | 0.3 | 1.8 | 73.8 | 75.2 | 76.6 | - | | | | 3.0 | 4.0 | 5.0 | 6.6 | | | | |
| REST1_SC2 | 15.95 | 1 | 2 | 7.97 | 0.50 | 0,5 | 14. O | 67,0 | 69.0 | 71.0 | 73.3 | | | | 3.0 | 3.9 | 4.9 | 6.3 | 10.0 | | | |
| REST5_SC9 | 79.73 | 5 | 9 | 8.86 | 0.56 | 0.8 | 7.2 | 61.1 | 63.7 | 66.3 | 69.2 | | | | 2.9 | 3.8 | 4.8 | 6.1 | 9.1 | | | |
| REST4_SC7 | 63.78 | 4 | 7 | 9.11 | 0.57 | 0.9 | 5.3 | 59.5 | 62.3 | 65.0 | 68.1 | | | | 2.9 | 3.8 | 4.7 | 6.1 | 9.0 | | | |
| REST3_SC5 | 47.84 | 3 | 5 | 9.57 | 0.60 | 1.0 | 12.1 | 56.8 | 59.9 | 62.9 | 66.2 | | | | 2.9 | 3.8 | 4.7 | 6.0 | 8.7 | | | |
| REST5_SC8 | 79.73 | 5 | 8 | 9.97 | 0.63 | 1.2 | 9.4 | 54.5 | 57.9 | 61.2 | 64.7 | | | | 2.9 | 3.8 | 4.7 | 6.0 | 8.6 | | | |
| REST2_SC3 | 31.89 | 2 | 3 | 10.63 | 0,67 | 1.4 | .5.1 | 51.0 | 54.8 | 58.4 | 62.4 | | | | 2.9 | 3.7 | 4.6 | 5.9 | 8.3 | | | |
| REST5_SC7 | 79.73 | 5 | 7 | 11.39 | 0.71 | 1.6 | .0.3 | 47.1 | 51.5 | 55.5 | 60.0 | | | | 2.9 | 3.7 | 4.6 | 5.8 | 8.? | | | |
| REST3_SC4 | 47.84 | 3 | 4 | 11.96 | 0.75 | 1.8 | 6.7 | 44.3 | 49.1 | 53.5 | 58.3 | | | | 2.9 | 3.7 | 4.5 | 5.8 | 8.0 | | | |
| REST4_SC5 | 63.78 | 4 | 5 | 12.76 | 0.80 | 2,0 | 1.7 | 40.6 | 46.0 | 50.9 | 56.0 | | | | 2.9 | 3.7 | 4.5 | 5.7 | 7.8 | | | |
| REST5_SC6 | 79.73 | 5 | 6 | 13.29 | 0,83 | 2,2 | 8.2 | 38.2 | 44.0 | 49.2 | 54.7 | | | | 2.8 | 3.7 | 4.5 | 5.7 | 7.8 | | | |
| **REST6_SC7** | 95.67 | 6 | 7 | 13.67 | 0.86 | 2,3 | 5.7 | 36.5 | 42.6 | 48.0 | 53.7 | | | | 2.8 | 3.7 | 4.5 | 5.6 | 7.7 | | | |
| **INCLINED OR EQUATORIAL SEQUENCES*** | | | | | | | | | | | | | | | | | | | | | | |
| REST1_SC1 | 15.95 | 1 | 1 | 15.95 | 1.00 | 2.9 | | 26.2 | 34.8 | 41.7 | 48.7 | 59.1 | - | | | 3.6 | 4.4 | 5.5 | 7.5 | 8.4 | | |
| REST5_SC4 | 79.73 | 5 | 4 | 19.93 | 1.25 | 3.7 | | | 21.5 | 32.3 | 41.6 | 54.4 | 57.0 | | | | 4.3 | 5.4 | 7.2 | 4.5 | 20.0 | |
| REST4_SC3 | 63.78 | 4 | 3 | 21.26 | 1.33 | 3,9 | | | 16.4 | 29.4 | 39.5 | 53.1 | 55.9 | | | | 4.3 | 5.3 | 7.1 | 4.1 | 18.4 | |
| REST7_SC5 | 111.62 | 7 | 5 | 22.32 | 1,40 | 4.1 | | | 11,4 | 27.1 | 38.0 | 52.2 | 55.0 | | | | 4.3 | 5.3 | 7.1 | 3.8 | 17.6 | |
| REST3_SC2 | 47.84 | 3 | 2 | 23.92 | 1.50 | 4.4 | | | | 23.6 | 35.8 | 50.9 | 53.9 | | | | | 5.3 | 7.0 | 3,5 | 16.8 | |
| **REST8_SC5** | 127.56 | 8 | 5 | 25.51 | 1.60 | 4.6 | | | | 20.1 | 33.8 | 49.7 | 52.8 | | | | | 5.3 | 7.0 | 3.2 | 16.3 | |
| REST5_SC3 | 79.73 | 5 | 3 | 26.58 | 1.67 | 4.7 | | | | 17.6 | 32.5 | 49.0 | 52.1 | | | | | 5.2 | 6.9 | 13.0 | 6.0 | |
| REST7_SC4 | 111.62 | 7 | 4 | 27.90 | 1.75 | 4.9 | | | | 14.2 | 30.9 | 48.1 | 51.4 | | | · | · | 5.2 | 6.9 | 12.9 | 5.7 | |
| REST9_SC5 | 143.51 | 9 | 5 | 28.70 | 1.80 | 5.0 | | | | 11.8 | 30.0 | 47.6 | 50.9 | 56.4 | | | | 5.2 | 6.9 | 12.8 | 5.5 | 28.2 |
| REST2_SC1 | 31.89 | 2 | 1 | 31.89 | 2.00 | 5.3 | | | · | · | 26.5 | 45.8 | 49.4 | 55.2 | | | - | - | 6.8 | 12.5 | 5.0 | 23.6 |
| REST9_SC4 | 143.51 | 9 | 4 | 35.88 | 2.25 | 5.7 | | | · | · | 22.3 | 43.9 | 47.7 | 53.8 | | | - | - | 6.7 | 12.2 | 4.5 | 21.7 |
| REST5_SC2 | 79.73 | 5 | 2 | 39.86 | 2.50 | 6.0 | | · | · | - | 18.1 | 42.3 | 46.3 | 52.7 | | | - | - | 6.7 | 12.0 | 4.2 | 20.6 |
| REST3_SC1 | 47.84 | 3 | 1 | 47.84 | 3.00 | 6.5 | | | · | · | 8.1 | 39.6 | 43.9 | 50.8 | | | - | - | 6.6 | 11.7 | 13.7 | 19.4 |
| REST4_SC1 | 63.78 | 4 | 1 | 63.78 | 4.00 | 7,1 | | | · | · | · | 35,7 | 40.6 | 48.3 | | - | - | - | | 11.3 | 13.2 | 18.2 |
| REST5_SC1 | 79.73 | 5 | 1 | 79.73 | 5.00 | 7.6 | | | · | · | · | 33.0 | 38.4 | 46.5 | | | | | | 11.1 | 12.9 | 17.5 |

*NOTE: These orbit periods may be used at either high or low inclinations.
Data to the right of the double vertical line pertains only to high inclinations, however.