JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 40, No. 4, July–August 2003

# Feasibility of a Galileo-Style Tour of the Uranian Satellites

Andrew F. Heaton*
*Marshall Space Flight Center, Huntsville, Alabama 35812*
and
James M. Longuski†
*Purdue University, West Lafayette, Indiana 47907-1282*

**Gravity-assist trajectories have been a key to outer solar system exploration. In particular, the gravity-assist tour of the Jovian satellites has contributed significantly to the success of the Galileo mission. A comparison of the Jovian system to the Uranian system reveals that the two possess similar satellite/planet mass ratios. Tisserand graphs of the Uranian system also indicate the potential for tours at Uranus. In this paper we devise tour strategies and design a prototypical tour of the Uranian satellites, demonstrating that tours at Uranus are feasible. In an example tour that launches in 2008, a series of flybys with Titania are used to reduce the inclination (14 deg at arrival) to permit encounters with Oberon, Ariel, and Umbriel. The tour involves over 40 flybys and ends after two years with a hyberbolic excess velocity with respect to Ariel of 0.92 km/s, which permits insertion into orbit about Ariel.**

## Nomenclature

| | | |
|---|---|---|
| $R_J$ | = | Jovian radius (71,492 km) |
| $R_P$ | = | flyby altitude, km |
| $R_{PT}$ | = | flyby altitude at Titania, km |
| $R_{PU}$ | = | flyby altitude at Ganymede, km |
| $R_U$ | = | Uranian radius (25,559 km) |
| $V_\infty$ | = | hyperbolic excess velocity, km/s |
| $\Delta V$ | = | delta velocity, km/s |
| $\delta$ | = | bending angle, rad |
| $\theta$ | = | B-plane angle, deg |
| $\mu$ | = | gravitational parameter, km$^3$/s$^2$ |
| $\mu_G$ | = | gravitational parameter of Ganymede, km$^3$/s$^2$ |
| $\mu_T$ | = | gravitational parameter of Titania, km$^3$/s$^2$ |

## Introduction

THE study of gravity assists has a long and rich history. As long ago as 1889, Tisserand[1] (also see Ref. 2) explained how a close encounter with Jupiter would affect the orbit of a comet. As the space age advanced, several researchers developed methods of designing spacecraft trajectories in the solar system in the 1960s.[3–5] In the 1970s interest focused on sending a spacecraft to Jupiter for a tour of its satellites.[6,7] The Galileo mission resulted from these studies.[8] The primary Galileo mission has produced an outstanding volume of scientific discoveries at Jupiter.[9] Various extended missions for Galileo have continued to exploit the concept of the satellite tour with great success.[10]

When contemplating the great utility of the satellite tour concept for Jovian exploration, naturally we wonder about the feasibility of satellite tours of other giant planets in the solar system. A survey of the giant planet satellite systems reveals that, contrary to intuition, a Galileo-style tour is possible at Uranus.[11] (Because they only possess one satellite each capable of providing a significant gravity assist, the satellite systems of Saturn and Neptune cannot support a Galileo-style tour.) That such a feat seems unlikely at Uranus is because the Uranian satellites are much less massive than those of Jupiter. However, the key for a significant gravity assist is not the absolute size of the satellite, but the ratio of its mass to the primary, and the mass ratios of the Uranian satellites to Uranus are similar to those of the Jovian satellites to Jupiter (see Table 1).

The semimajor axes of the satellites are also similar when scaled to the central planet's radius as shown in Table 2. Yet another common feature is that the two outermost satellites at Uranus (Titania and Oberon) are the most massive, and the two outermost satellites at Jupiter (Ganymede and Callisto) are also the most massive. In fact, there is a correlation between the mass ratios of the Jovian and Uranian satellites and their semimajor axis, with the exception of Ariel–Io. Starting with the respective innermost satellites and moving outwards, Ariel's mass ratio is 33% of Io's, Umbriel's is 54% of Europa's, Titania's is 53% of Ganymede's, and Oberon's is 61% of Callisto's (so the satellite mass ratios of each system are roughly correlated to their distance from the primary). In summary, the Uranian satellite system is nearly a smaller replica of the Jovian system as a result of the correlation between the satellite-to-primary mass ratios and the relative spacing of the satellites. Tables 1 and 2 suggest the feasibility of a Galileo-like tour at Uranus.

## Tisserand Graph Analysis

The Tisserand graph has been developed by researchers at Purdue University to facilitate gravity-assist tour design.[11–14] This method assumes circular, coplanar orbits for the satellites. Under these assumptions the geometry of the intersection of a given spacecraft orbit (i.e., with specified periapsis and period with respect to the primary) with the circular satellite orbit will be the same at any point in the satellite's orbit (because of the symmetry of a circular orbit). Therefore, the spacecraft will have the same $V_\infty$ with respect to the satellite at any point along the satellite's orbit. This means that the $V_\infty$ of the spacecraft orbit relative to any satellite is a function of only the spacecraft orbit periapsis and period. In essence, the Tisserand graph depicts the energy states of spacecraft orbits with respect to the primary in terms of the spacecraft $V_\infty$ with respect to the satellites. The spacecraft orbit is confined to move along constant $V_\infty$ contours for a given gravity-assist flyby. Tick marks on the $V_\infty$ contours distinguish how much change is possible from a single flyby at a given altitude. Where the spacecraft orbit crosses the $V_\infty$ contour of a different satellite, we can attempt to target a flyby of that satellite as well. By stringing together several flybys of the various satellites, we specify (to a large degree) the final orbital energy. The Tisserand graph serves as a map to enable us to judiciously choose promising flyby sequences. Once the flyby sequence, or path, is selected, the Satellite Tour Design Program[15–18]

Received 10 October 2002; revision received 6 March 2003; accepted for publication 14 March 2003. 

*Aerospace Engineer, Guidance Navigation and Controls Group, Mail Stop TD54; andrew.f.heaton@nasa.gov. Member AIAA.

†Professor, School of Aeronautics and Astronautics, 1282 Grissom Hall; longuski@ecn.purdue.edu. Associate Fellow AIAA.

**Table 1 Mass ratio comparison**

| Satellite | $\mu$, km$^3$/s$^2$ | Mass ratio of satellites/primary body |
|---|---|---|
| Uranian | | |
| Ariel | 98.5 | 1.56 $(10^{-5})$ |
| Umbriel | 78.3 | 1.35 $(10^{-5})$ |
| Titania | 235 | 4.06 $(10^{-5})$ |
| Oberon | 201 | 3.47 $(10^{-5})$ |
| Jovian | | |
| Io | 5934 | 4.68 $(10^{-5})$ |
| Europa | 3196 | 2.52 $(10^{-5})$ |
| Ganymede | 9885 | 7.80 $(10^{-5})$ |
| Callisto | 7172 | 5.66 $(10^{-5})$ |

**Table 2 Semimajor axis comparison**

| Satellite | Semimajor axis (in primary radii) |
|---|---|
| Uranian | $(R_U)$ |
| Ariel | 7.45 |
| Umbriel | 10.58 |
| Titania | 17.38 |
| Oberon | 23.24 |
| Jovian | $(R_J)$ |
| Io | 5.91 |
| Europa | 9.39 |
| Ganymede | 14.98 |
| Callisto | 26.35 |

(STOUR) determines whether the phasing between the various satellites will allow transfers between them. (The program STOUR is an automated design tool that uses patched conics to search over the large number of possible paths for gravity-assist tours of satellites systems and in the solar system.) STOUR has been used in the design of the Galileo orbital tour (for which the tool was originally created) and Europa Orbiter tour design studies. It has been found that the patched conic designs agree well with refined numerically integrated trajectories. The flyby distances and times can typically vary by several tens of kilometers for close encounters (hundreds for distant encounters) and a few hours. The most important design experience with this software is that all conic trajectories have analogs that are very similar to numerically integrated results. A more detailed explanation of Tisserand graphs can be found in Heaton et al.[12] and Strange and Longuski.[13] This graphical method has been used with great success to design Europa Orbiter tours and is similar to a method developed by Labunsky et al.[19] The method takes its name from Tisserand, who in 1889 used a similar relationship (Tisserand's criterion) to explain perturbations of comets by Jupiter.[1]

Tisserand graphs for Jupiter and Uranus are shown in Figs. 1 and 2, respectively. We see immediately that these two graphs strongly resemble each other. Some differences also exist, however. First and foremost, the tick marks in the Uranian plot (Fig. 2) are closer together (which agrees well with the mass ratio data presented in Table 1 because closer tick marks reflect the smaller masses of the Uranian system). The slopes of the $V_\infty$ contours of Oberon are slightly higher than those of Callisto. The same is true of Titania as compared to Ganymede because the Uranian satellites are relatively farther from the central body. One common factor between the two systems is that the two outermost satellites are the most effective gravity-assist bodies. All of the Uranian satellites have less potential for gravity-assist flybys, but the difference in potential is more marked for Umbriel and Ariel (when compared to Europa and Io, respectively) than it is for Titania and Oberon (when compared to Ganymede and Callisto, respectively). Another difference is that the satellite-relative $V_\infty$ range at Uranus is smaller. This is because Uranus has a smaller gravitational parameter and also implies that insertion into Uranian orbit is costlier than insertion into Jovian orbit.

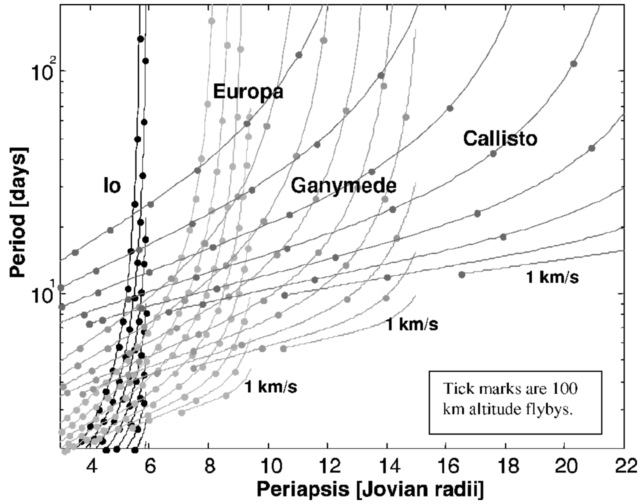


**Fig. 1 Jovian Tisserand graph with $V_\infty$ increments of 1 km/s for each satellite.**

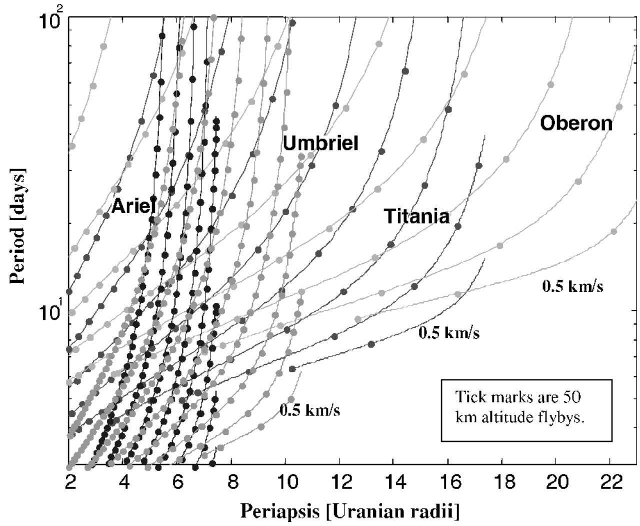


**Fig. 2 Uranian Tisserand graph with $V_\infty$ increments of 0.5 km/s for each satellite.**

## Arrival Geometry and Initial Conditions

Uranus has an obliquity of 97 deg, and its satellites remain close to the equatorial plane. Thus, any spacecraft arriving at Uranus is likely to have a high-inclination initial condition with respect to the satellites. Figure 3 illustrates the arrival geometry problem in more detail for a Hohmann transfer to Uranus from Earth. For certain arrival dates (e.g., February 2028 and March 2070) the arrival $V_\infty$ vector coincides with a "zero-inclination insertion," thereby resulting in great savings in $\Delta V$ (i.e., no propellant cost to place the spacecraft into the satellite plane). Although useful for illustrating the problem of high inclination at Uranus, the Hohmann transfer is not a viable option for a mission to Uranus because it has a time of flight of 16 years. A faster trajectory to Uranus, however, implies a different arrival $V_\infty$ vector, thereby changing the arrival conditions depicted in Fig. 3 and creating the possibility of arriving on different dates with a low inclination.

The complex relationship between launch date, arrival date, arrival $V_\infty$ vector, arrival geometry, and launch energy is explored in detail in Ref. 11. The purpose of studying these relationships is to provide a realistic initial orbit at Uranus as a starting point for tour design and also one that is achievable with current technology. Given current constraints on launch energy and upcoming launch windows, we found that a Jupiter gravity assist to Uranus appears to be the best option. With this option flight times of about 10 years to Uranus are achievable with launch capability that is available today.

**Table 3 Ariel orbiter design reference mission**

| Event | Date, month/day/year | $V_\infty$, km/s |
|---|---|---|
| Launch | 3/19/2008 | 9.80 |
| Jupiter flyby | 9/13/2009 | 11.11 |
| Uranus arrival | 2/14/2018 | 6.44 |
| Titania arrival | 5/2/2019 | 3.27 |

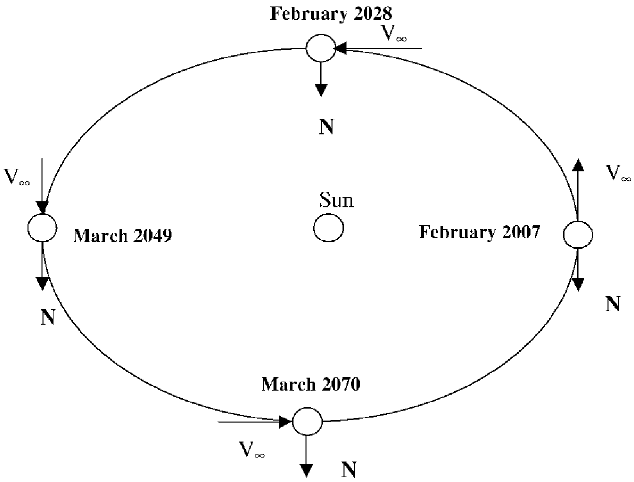


**Fig. 3 Hohmann arrival vector $V_\infty$ migration with respect to Uranian North pole vector.**

Given launch constraints and the results of studies of Jupiter gravity assists, we limit insertion $\Delta V$ at Uranus to below 2.5 km/s, which implies an arrival $V_\infty$ at Uranus of less than 7.5 km/s. A series of trade studies with STOUR incorporating all of these considerations yields a design reference mission that we use to derive the initial orbit of the tour (see Table 3 for details). The window for a Jupiter gravity assist to Uranus closes in 2008. The optimal Jupiter gravity assist to Uranus cycles approximately every 14 years, and so the next similar launch opportunity will occur in 2022. By that time the plane containing the Uranian satellites will have precessed to a less desirable angle for the arrival $V_\infty$ geometry. The Uranian satellite plane moves a little over 4 deg per year with respect to the Uranus–sun line (and so with respect to any arriving spacecraft; see Fig. 3). The motion of the Uranian satellite plane after 2019 is in a direction that causes the inclination of the insertion orbit to grow larger. The amount of $\Delta V$ necessary to change the inclination of the orbit increases as the sine of the insertion orbit inclination. Thus, launch delays past 2008 result in steadily increasing $\Delta V$.

## Rationale for a Uranian Orbiter

There are many tantalizing scientific objectives at Uranus.[20] Uranus is often considered "bland" and uninteresting, in part because of the quiescence of its atmosphere during the Voyager 2 flyby.[21] However, recent investigations by the Hubble Space Telescope indicate that the weather on Uranus is "heating up" as the planet approaches vernal equinox,[22] generating atmospheric phenomena not present during the flyby. Furthermore, the deep grooves and chevrons of Miranda have led to speculation in the planetary community as to the origin and subsequent evolution of this most interesting satellite.[20] Finally, we observe that Uranus is much closer and easier to reach than its far outer planet companions Neptune and Pluto. Indeed, when we consider that Galileo launched to Jupiter in the 1980s and arrived in the 1990s, while Cassini launched to Saturn in the 1990s and is scheduled to arrive in 2004, Uranus is clearly the next logical candidate[23] in the "outer planets orbiter series."

## Guidelines and Constraints for Uranian Tour Design

In this section we select guidelines and constraints for a Uranian tour and compare and contrast some of them with those of the Europa Orbiter tour.[24] In our selection we incorporate some of the recommendations of Wallace[25] and Wallace et al.[26]

What mission guidelines should the tour follow? Is it a general tour of the Uranian system similar to that of the Galileo spacecraft, or does it have a specific destination as in the case of the Europa Orbiter? We elect to use the techniques first developed in the Galileo mission, but in addition we adopt the highly focused goal of the Europa Orbiter mission of reducing $V_\infty$ at a destination satellite. We choose, as the goal for the Uranian Orbiter, that the $V_\infty$ of arrival at Ariel be less than 1 km/s. Thus, at the end of the tour the spacecraft could be inserted into orbit about Ariel. If we can demonstrate the existence of such a tour, then many other tours with less stringent requirements can be designed.

Now that our hypothetical tour has an objective, guidelines and constraints can be selected. The limit on the periapsis of any orbit in the tour will be 4 $R_U$, based on the maximum radius of the Uranian rings (about 3.4 $R_U$). The inclination of the initial orbit at Uranus should be less than 20 deg, based on a trade study which shows that approximately one year of "orbit cranking" (a flyby that changes only inclination) is required to bring a 20-deg inclined orbit into the equatorial plane (where the satellites reside).[11] Larger inclinations require too much time in the orbit-cranking phase. We estimate that a Uranian tour will take about two years, twice as long as a typical Europa Orbiter tour. We require each orbit of the Uranian tour to pass through apoapsis between each flyby to allow sufficient time for trajectory-correction maneuvers.

The Uranian satellite system is a scaled-down version of the Jovian system. This fact implies that nontargeted encounters occur more frequently at Uranus because the satellites are closer to each other. Tour design experience has shown that this is, indeed, the case. So the question arises, what is an acceptable flyby distance for a nontargeted encounter at Uranus? To answer this question, we consider the well-known equation for the maximum deflection angle possible for a given flyby:

$$\sin(\delta/2) = 1\big/\left(1 + V_\infty^2 R_P\big/\mu\right) \tag{1}$$

The acceptable flyby distance for nontargeted flybys in the Jovian system is 50,000 km.[24] We will compare Ganymede and Titania, the most massive satellites of their respective planets. By assuming that the $\delta$ and $V_\infty$ have the same values in the Jovian and Uranian systems, Eq. (1) provides

$$R_{\text{PT}}/R_{\text{PG}} = \mu_T/\mu_G \tag{2}$$

Equation (2) indicates that the flyby distance for a given amount of bending (and the same $V_\infty$) is a function of only the mass ratios of the bodies being compared. The ratio of Ganymede's mass to that of Titania is about 42:1, and so the equivalent flyby distance at Titania for the same amount of bending is 1200 km. However, the same bending at Uranus has a greater effect on the spacecraft's orbit than a similar amount of bending at Jupiter because Uranus is less massive than Jupiter. Taking into account the lower gravity of Uranus, we find that nontargeted flybys of Titania at 10,000 km correspond to flybys of Ganymede at 50,000 km. Hence, we constrain nontargeted flybys of Uranian satellites to be greater than 25,000 km, which corresponds (with conservative margin) to the soft limit of 100,000 km for nontargeted flybys in the Jovian system.

The final constraint that must be decided is the flyby altitude. Because the satellites of Uranus are much less massive than those of Jupiter, closer flybys are in general required at Uranus. For this reason, the flyby altitude is set to 50 km for the Uranian tour. This constraint certainly pushes the limits of what is navigationally feasible. For our prototype tour the impact of raising the altitude limit to 100 km (the flyby altitude limit for the Europa Orbiter[24]) is that more flybys would be required over the course of the tour, lengthening the time of flight. Table 4 presents a summary of all of the guidelines and constraints derived in this section.

## Uranian Tour Example

We now present a Uranian tour design to demonstrate the feasibility of the concept. Our tour involves three phases: the initial or

**Table 4 Guidelines and constraints summary for an Ariel orbiter**

| Constraint/guideline | Value |
|---|---|
| Arrival $V_\infty$ | <1 km/s |
| Periapsis constraint | >4 $R_U$ |
| Initial inclination | <20 deg |
| Nontargeted flybys | >25,000 km |
| Flyby altitude | >50 km |
| Time of flight | <2.5 years |

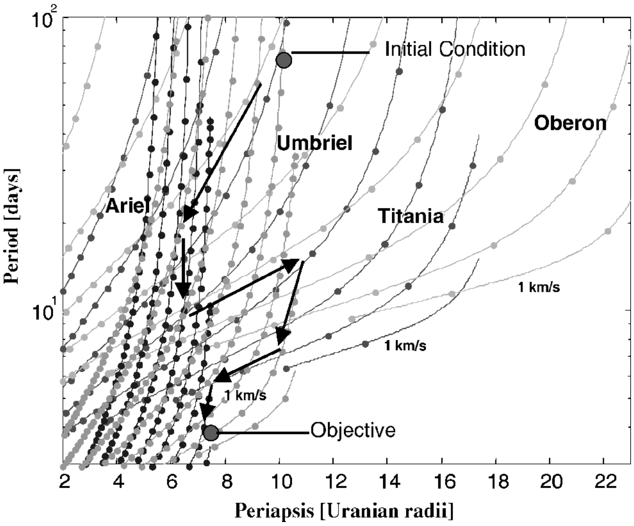


**Fig. 4 Uranian Tisserand graph illustrating the strategy employed for Uranian tour design.**

inclination-reduction phase, the middle or energy-reduction phase, and the end or Ariel-rendezvous phase.

The inclination-reduction phase addresses the problem of high initial inclination discussed earlier. The problem is solved through a series of resonant flybys to crank down the inclination of the orbit. Our trade studies of Ariel and Titania indicate that Titania is more effective for orbit cranking, requiring fewer flybys and less time. This result might be expected because of Titania's greater mass and similarity to Ganymede, which is the best Jovian satellite for reducing inclination. Although Ariel seems to offer better energy reduction from the steepness of its curves on the Uranian Tisserand graph, this potential advantage proves to be insufficient justification for the longer time of flight and greater number of flybys required at Ariel for the crank-down. Thus, we choose Titania as the first flyby body for our tour design at Uranus.

Once the inclination-reduction phase of the tour is complete, the next step is to select a path for the energy-reduction phase, which is the middle part of the tour. As with the Europa Orbiter design, this is the least constrained of the three phases because a large number of paths are possible. Tour design strategy in the energy-reduction phase consists of reducing the energy of the orbit while setting up the right conditions to begin the end or Ariel-rendezvous phase of the tour.

The Ariel-rendezvous phase of the tour is essentially determined by the orbit state of the final objective (i.e., the location of the final orbit on a Tisserand graph). The final orbit state by its very nature determines the last few flybys of the tour. For instance, in design studies[12,24] the Europa Orbiter tour typically ends with a transfer from Callisto to Ganymede, multiple resonant flybys of Ganymede, and then a transfer from Ganymede to Europa. We can anticipate that a similar end-of-tour strategy can be developed for our objective of achieving a low arrival $V_\infty$ at Ariel (less than 1 km/s). Another way of thinking about our goal in terms of the Tisserand graph is to say that we are attempting to achieve an orbit that is as close to coorbital with Ariel as possible.

We can now explain the various phases of the tour design process and derive a tour design strategy with the Uranian Tisserand graphs. Figure 4 is a Uranian Tisserand graph that includes the initial condition, the mission objective, and a general strategy of path selection for all three phases. This suggested design strategy is only a first-glance, "broad brush" assessment of what is possible. The inclination-reduction phase is represented in Fig. 4 as the first arrow from the top. The second arrow from the top begins the energy-reduction phase of the tour, using Umbriel and Ariel to pump down the energy of the orbit while maintaining a relatively high periapsis (>4 $R_U$). The next three arrows in the progression indicate the strategy for the rest of the energy-reduction phase and are not intended to represent the actual path selection (because many paths are possible in the middle part of the tour). Rather, these three arrows show how the tour must move to the right on the Tisserand graph in order to reach the mission objective of $V_\infty < 1$ km/s at Ariel while maintaining periapsis >4 $R_U$. In general, in the energy-reduction phase of the tour design, Oberon is used to pump up because it increases periapsis significantly, while pumping up the period minimally. Thus Oberon is used mainly for periapsis maintenance. On the other hand, Titania and Umbriel are used to pump down because their slopes on the Tisserand graph provide for significant period reduction with minimal periapsis reduction.

The end phase or Ariel-rendezvous phase for the tour at Uranus is more flexible than the end phase for the Europa Orbiter. The end of the Uranian tour is less constrained because the lack of a radiation constraint at Uranus allows the Ariel-rendezvous phase flybys to use Umbriel (which is closer to Uranus than Titania) extensively, whereas at Jupiter the need to keep the periapsis as high as possible limited the use of multiple Ganymede–Europa transfers for the final approach to Europa. So, for the Ariel-rendezvous phase of tour design at Uranus the final approach can use Titania, Umbriel, or a combination thereof. (Oberon is not an option because no orbit from Oberon can reach Ariel with an arrival $V_\infty < 1$ km/s.) The theoretical best arrival $V_\infty$ at Ariel is 0.46 km/s, via a Hohmann transfer from Umbriel, whereas the Hohmann transfer from Titania results in a $V_\infty$ of arrival at Ariel of 1.00 km/s.

The tour that appears in Table 5 was designed using the strategy just described. This tour is designated U00-01, for the first Uranian tour designed in 2000. Tour U00-01 uses nine flybys and requires 261 days to eliminate the initial inclination of 13.6 deg. Although nine flybys are more than required for inclination reduction in any Europa Orbiter tour, nine is not an unreasonable number. The first phase of the tour certainly demonstrates that such a large inclination can be accommodated. The first nine orbits of the inclination-reduction phase are presented graphically in Fig. 5. We found it more efficient to reduce the energy (and hence period) of the initial orbit with the first four flybys and to use the next five flybys to reduce inclination only. The effect on the orbits between each flyby can be clearly discerned from the plot, with a comparison of orbits 1–4 illustrating a reduction in orbit size from each flyby, whereas orbits 5–9 remain essentially the same size while the inclination is greatly reduced.

Events 11–32 in Table 5 represent the energy-reduction phase of the tour. This phase makes extensive use of Ariel itself for pump

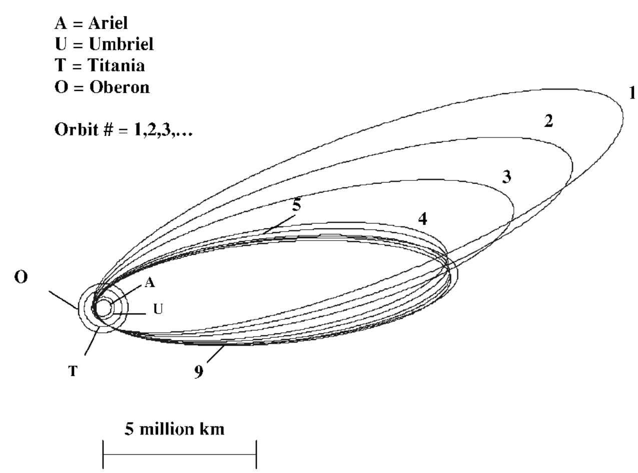


**Fig. 5 First nine orbits of Tour U00-01 (inclination-reduction phase).**

**Table 5 Tour U00-01 summary**

| Event #/satellite | Altitude, km | $\theta$,[a] deg | $V_\infty$, km/s | Period, days | Periapsis, $R_U$ | Time, days |
|---|---|---|---|---|---|---|
| 1/Titania | 316 | −22 | 3.27 | 52.2 | 9.1 | 0 |
| 2/Titania | 74 | −65 | 3.27 | 43.5 | 8.6 | 52.2 |
| 3/Titania | 58 | −54 | 3.27 | 34.8 | 8.1 | 95.8 |
| 4/Titania | 54 | −23 | 3.27 | 26.1 | 7.4 | 130.6 |
| 5/Titania | 90 | −92 | 3.28 | 26.1 | 7.2 | 156.7 |
| 6/Titania | 90 | −92 | 3.28 | 26.1 | 7.0 | 182.8 |
| 7/Titania | 90 | −91 | 3.29 | 26.1 | 6.9 | 208.9 |
| 8/Titania | 90 | −91 | 3.30 | 26.1 | 6.8 | 235.1 |
| 9/Titania | 776 | −103 | 3.30 | 27.0 | 6.9 | 261.2 |
| 10/Oberon | 414 | 0 | 2.98 | 23.2 | 6.3 | 287.6 |
| 11/Ariel | 378 | 0 | 3.04 | 20.2 | 6.2 | 312.2 |
| 12/Ariel | 55 | 0 | 3.04 | 16.7 | 6.1 | 332.4 |
| 13/Titania | 388 | 0 | 3.18 | 14.5 | 5.7 | 348.2 |
| 14/Umbriel | 54 | 180 | 3.64 | 13.2 | 5.5 | 364.3 |
| 15/Oberon | 584 | 0 | 2.60 | 14.5 | 6.1 | 378.7 |
| 16/Ariel | 133 | 180 | 2.99 | 12.6 | 6.0 | 406.2 |
| 17/Ariel | 219 | 180 | 2.99 | 11.2 | 6.0 | 418.8 |
| 18/Ariel | 119 | 0 | 2.99 | 9.9 | 5.9 | 440.7 |
| 19/Oberon | 109 | 180 | 2.13 | 11.5 | 7.1 | 448.9 |
| 20/Ariel | 651 | 0 | 2.00 | 8.8 | 7.0 | 473.6 |
| 21/Ariel | 88 | 180 | 1.87 | 10.2 | 7.1 | 491.3 |
| 22/Ariel | 251 | 0 | 1.86 | 11.4 | 7.2 | 501.8 |
| 23/Oberon | 282 | −12 | 2.10 | 12.5 | 9.0 | 526.5 |
| 24/Umbriel | 432 | −101 | 1.97 | 12.8 | 9.0 | 561.6 |
| 25/Umbriel | 196 | 180 | 1.97 | 11.3 | 8.9 | 575.2 |
| 26/Oberon | 404 | 180 | 1.78 | 13.2 | 10.3 | 583.8 |
| 27/Umbriel | 60 | 0 | 1.20 | 11.8 | 10.2 | 599.2 |
| 28/Titania | 286 | 0 | 1.93 | 9.7 | 9.0 | 609.8 |
| 29/Oberon | 241 | 180 | 1.44 | 11.7 | 11.2 | 637.7 |
| 30/Titania | 342 | 0 | 1.72 | 9.5 | 9.9 | 662.1 |
| 31/Umbriel | 166 | 180 | 1.29 | 8.3 | 9.7 | 682.8 |
| 32/Umbriel | 151 | 180 | 1.29 | 7.3 | 9.5 | 691.1 |
| 33/Titania | 909 | 138 | 1.30 | 9.9 | 13.3 | 696.1 |
| 34/Titania | 1293 | 139 | 1.04 | 8.7 | 12.2 | 709.2 |
| 35/Titania | 95 | −180 | 1.04 | 6.5 | 9.3 | 717.9 |
| 36/Titania | 2189 | −173 | 1.04 | 6.1 | 8.4 | 744.0 |
| 37/Umbriel | 238 | −180 | 1.61 | 5.5 | 8.1 | 760.7 |
| 38/Umbriel | 77 | −180 | 1.61 | 5.0 | 7.7 | 777.2 |
| 39/Umbriel | 519 | −180 | 1.61 | 4.7 | 7.5 | 802.1 |
| 40/Ariel | 316 | —— | 0.92 | —— | —— | 810.8 |

[a]$\theta$ is the angle in the plane perpendicular to the incoming $V_\infty$ vector, where values of 0 and 180 deg correspond (approximately) to equatorial flybys and −90 and +90 deg correspond (approximately) to flybys over the north and south poles of the satellite, respectively.

downs. Many of these flybys are nonresonant. Resonant flybys are more difficult to achieve for Uranian satellites than Jovian satellites because of the weaker gravity of the Uranian satellites (i.e., the tick marks on the Tisserand graph are closer together). Therefore, in Tour U00-01 nonresonant "repeat" flybys are used at every satellite with the exception of Oberon. The energy-reduction phase achieves its goal of setting up the tour for the Ariel-rendezvous phase, but by no means is the energy-reduction phase optimized for number of flybys or the best path selected because Tour U00-01 is intended only as a demonstration of feasibility.

The Ariel-rendezvous phase of U00-01 occurs between events 32 and 40 and consists of multiple flybys of Titania followed by multiple flybys of Umbriel with a final transfer orbit from Umbriel to Ariel. A close inspection of Fig. 4 reveals that this is the natural path to follow from energy considerations. Again, many of the multiple flybys of Titania and Umbriel in the Ariel-rendezvous phase are nonresonant. The end phase achieves a $V_\infty$ of 0.92 km/s at Ariel (which is sufficiently below the 1-km/s goal).

## Conclusions

This paper demonstrates, for the first time, that a Galileo-style tour is possible at Uranus. Such a mission follows the logical progression after Galileo at Jupiter and Cassini at Saturn. The large obliquity of Uranus constrains launch windows to open every 42 years (roughly half the orbital period of Uranus). Because the four major satellites of Uranus have only half the relative masses with respect to Uranus that the Jovian satellites have with respect to Jupiter, a Uranian tour requires more gravity-assist encounters than a similar Jovian tour if an orbital mission at Ariel is desired. Such a mission at the Uranian system would require about 2.5 years for a launch window in 2008. Beyond this opportunity, arrival inclination significantly increases, and the tour mission would take longer. A similar tour opportunity will not occur again for several decades.

## Acknowledgments

This work was made possible by a Full Time Study Fellowship from the NASA Marshall Space Flight Center. We particularly thank Lewis Wooten, Patricia Avery, and Irene Taylor for the approval of leave and managerial support, as well as Gerald Miller for programmatic support. We thank Anastassios Petropoulos for his contribution to the development of the Tisserand graph while a doctoral candidate at Purdue University. We also thank Alex Blackwell for providing scientific references for Uranus. This paper was presented as Paper AAS 01-468 at the AAS/Astrodynamics Specialist Conference, Quebec City, Quebec, Canada, 30 July–2 August 2001.

## References

[1]Tisserand, F., *Traite de Mechanique Celeste*, Guthier-Villar et Fils, Imprimeurs-Libraires, Paris, 1896, pp. 214–216.

[2]Roy, A. E., *Orbital Motion*, 2nd ed., Adam Hilger, Bristol, England, U.K., 1982, pp. 129, 130.

[3]Minovitch, M. A., "The Determination and Characteristics of Ballistic Interplanetary Trajectories Under the Influence of Multiple Planetary Attractions," Jet Propulsion Lab., California Inst. of Technology, Technical Rept. 32-464, Pasadena, CA, Oct. 1964.

[4]Niehoff, J. C., "Gravity-Assisted Trajectories to Solar System Targets," *Journal of Spacecraft and Rockets*, Vol. 3, No. 9, 1966, pp. 1351–1356.

[5]Flandro, G. A., "Fast Reconnaissance Missions to the Outer Solar System Utilizing Energy Derived from the Gravitational Field of Jupiter," *Astronautica Acta*, Vol. 12, No. 4, 1966, pp. 329–337.

[6]Beckman, J. C., and Smith, D. B., "The Jupiter Orbiter Satellite Tour Mission," American Astronautical Society, Paper AAS 73-231, July 1973.

[7]Uphoff, C., Roberts, P. H., and Friedman, L. D., "Orbit Design Concepts for Jupiter Orbiter Missions," *Journal of Spacecraft and Rockets*, Vol. 13, No. 6, 1976, pp. 348–355.

[8]Diehl, R. E., Kaplan, D. I., and Penzo, P. A., "Satellite Tour Design for the Galileo Mission," AIAA Paper 83-0101, Jan. 1983.

[9]Belton, M. J. S. (ed.), "Special Issue on Remote Sensing Results of the Galileo Orbiter Mission," *Icarus*, Vol. 135, No. 1, 1998, pp. 1–180.

[10]Bell, J. L., and Johannesen, J. R., "Galileo Europa Mission (GEM) Tour Design," American Astronautical Society, Paper AAS 97-614, Aug. 1997.

[11]Heaton, A. F., "A Systematic Method for Gravity-Assist Tour Design," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Dec. 2000.

[12]Heaton, A. F., Strange, N. J., Longuski, J. M., and Bonfiglio, E., "Automated Design of the Europa Orbiter Tour," *Journal of Spacecraft and Rockets*, Vol. 39, No. 1, 2002, pp. 17–22.

[13]Strange, N. J., and Longuski, J. M., "Graphical Method for Gravity-Assist Tour Design," *Journal of Spacecraft and Rockets*, Vol. 39, No. 1, 2002, pp. 9–16.

[14]Johnson, W., and Longuski, J. M., "Design of Aerogravity Assist Trajectories," *Journal of Spacecraft and Rockets*, Vol. 39, No. 1, 2002, pp. 23–30.

[15]Rinderle, E. A., "Galileo User's Guide, Mission Design System, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Lab., California Inst. of Technology, Internal Document D-263, Pasadena, CA, July 1986.

[16]Longuski, J. M., and Williams, S. N., "Automated Design of Gravity-Assist Trajectories to Mars and the Outer Planets," *Celestial Mechanics and Dynamical Astronomy*, Vol. 52, No. 3, 1991, pp. 207–220.

[17]Patel, M. R., and Longuski, J. M., "Automated Design of $\Delta V$ Gravity-Assist Trajectories for Solar System Exploration," American Astronautical Society Paper AAS 93-682, Aug. 1993.

[18]Bonfiglio, E. P., Longuski, J. M., and Vinh, N. X.,"Automated Design of Aerogravity-Assist Trajectories," *Journal of Spacecraft and Rockets*, Vol. 37, No. 6, 2000, pp. 768–775.

[19]Labunsky, A. V., Papkov, O. V., and Sukhanov, K. G., *Multiple Gravity Assist Interplanetary Trajectories*, 1st ed., Gordon and Breach, New York, 1998, pp. 101–197.

[20]Miner, E., *Uranus—The Planet, Rings, and Satellites*, Wiley, New York, 1998.

[21]Lindal, G. F., Lyons, J. R., and Sweetnam, D. N., "The Atmosphere of Uranus: Results of Radio Occultation Measurements with Voyager 2," *Journal of Geophysical Research*, Vol. 92, No. A13, 1987, pp. 14,987–15,001.

[22]Karkoschka, E., "Uranus' Apparent Seasonal Variability in 25 HST Filters," *Icarus*, Vol. 151, No. 1, 2001, pp. 84–92.

[23]Sykes, M. V. (ed.), *The Future of Solar System Exploration 2003-2013*, ASP Conference Series Vol. CS-272, Astronomical Society of the Pacific, San Francisco, 2002, pp. 190, 224, 225.

[24]Johanessen, J. R., and D'Amario, L. A., "Europa Orbiter Mission Trajectory Design," American Astronautical Society, Paper AAS 73-231, Aug. 1999.

[25]Wallace, R. A., "Uranus Mission Options," American Astronautical Society, Paper AAS 79-145, June 1979.

[26]Wallace, R. A., Lane, A. L., Roberts, P. H., and Snyder, G. C., "Missions to the Far Outer Planets in the 1990's," AIAA Paper 81-0311, Jan. 1981.

C. A. Kluever
*Associate Editor*